NRC·CNRC

NRC Publications Archive
Archives des publications du CNRC

Report on the investigation of lateral ice pressure techniques in model ice at the Institute for Marine Dynamics

Hardiman, K. C.

For the publisher's version, please access the DOI link below./ Pour consulter la version de l'éditeur, utilisez le lien DOI ci-dessous.

Publisher's version / Version de l'éditeur:
https://doi.org/10.4224/8895928
Contractor Report (National Research Council of Canada. Institute for Marine Dynamics); no. CR-1992-04, 1992

NRC Publications Archive Record / Notice des Archives des publications du CNRC :
https://nrc-publications.canada.ca/eng/view/object/?id=58746ec0-f1e6-43d9-9251-a1efe7b58376
https://publications-cnrc.canada.ca/fra/voir/objet/?id=58746ec0-f1e6-43d9-9251-a1efe7b58376

Access and use of this website and the material on it are subject to the Terms and Conditions set forth at
https://nrc-publications.canada.ca/eng/copyright
READ THESE TERMS AND CONDITIONS CAREFULLY BEFORE USING THIS WEBSITE.

L'accès à ce site Web et l'utilisation de son contenu sont assujettis aux conditions présentées dans le site
https://publications-cnrc.canada.ca/fra/droits
LISEZ CES CONDITIONS ATTENTIVEMENT AVANT D'UTILISER CE SITE WEB.

Questions? Contact the NRC Publications Archive team at
PublicationsArchive-ArchivesPublications@nrc-cnrc.gc.ca. If you wish to email the authors directly, please see the first page of the publication for their contact information.

Vous avez des questions? Nous pouvons vous aider. Pour communiquer directement avec un auteur, consultez la première page de la revue dans laquelle son article a été publié afin de trouver ses coordonnées. Si vous n'arrivez pas à les repérer, communiquez avec nous à PublicationsArchive-ArchivesPublications@nrc-cnrc.gc.ca.

National Research Council Canada　Conseil national de recherches Canada

Canada

National Research Council Canada
Institute for Ocean Technology

Conseil national de recherches Canada
Institut des technologies océaniques

Contractor Report

CR-1992-04

Report on the Investigation of Lateral Ice Pressure Techniques in Model Ice at the Institute for Marine Dynamics

K. C. Hardiman

February 1992

Hardiman, K. C., 1992. Report on the Investigation of Lateral Ice Pressure Techniques in Model Ice at the Institute for Marine Dynamics. St. John's, NL : NRC Institute for Marine Dynamics, CR-1992-04.

Canada

REPORT ON THE INVESTIGATION OF LATERAL ICE PRESSURE TECHNIQUES IN MODEL ICE AT THE INSTITUTE FOR MARINE DYNAMICS

K.C. Hardiman

February 1992

Presented to:

Dr. Stephen Jones
Institute for Marine Dynamics
P. O. Box 12093
St. John's, Newfoundland
A1B 3T5

Prepared By:

Fleet Technology Newfoundland Limited
P.O. Box 5040
St. John's, Newfoundland
A1C 5V3

DOCUMENTATION PAGE

REPORT NUMBER CR-1992-04	NRC REPORT NUMBER -	DATE June 1992

REPORT SECURITY CLASSIFICATION Unclassified	DISTRIBUTION Unlimited

TITLE

REPORT ON THE INVESTIGATION OF LATERAL ICE PRESSURE TECHNIQUES IN MODEL ICE AT THE INSTITUTE FOR MARINE DYNAMICS

AUTHOR(S)

K.C. Hardiman

CORPORATE AUTHOR(S)/PERFORMING AGENCY(S)

Fleet Technology Newfoundland Limited

PUBLICATION

-

SPONSORING AGENCY(S)

Institute for Marine Dynamics
National Research Council Canada

IMD PROJECT NUMBER 304	NRC FILE NUMBER 7819		
KEY WORDS: pressured ice / ship resistance / ice modelling	**PAGES**	**FIGS.** 15	**TABLES** 10

SUMMARY:

This report presents the findings of the investigation of a simplified method for inducing in-plane lateral pressure in the model EG/AD/S ice in the Ice Tank at the Institute for Marine Dynamics.

ADDRESS: National Research Council
Institute for Marine Dynamics
P. O. Box 12093, Station 'A'
St. John's, NF
A1B 3T5

Acknowledgements:

The study team would like to thank Dr. Stephen Jones and the members of the Ice Group at the Institute for Marine Dynamics for their support and assistance during this project, as well as Mr. Razek Abdelnour for his assistance and technical guidance.

Summary:

This document reports the results of a series of "In-plane Ice Pressure Tests" conducted in the ice tank of the Institute for Marine Dynamics, St. John's, Newfoundland by Fleet Technology Newfoundland Limited to investigate a method to induce in-plane pressure in model EG/AD/s ice. This work was conducted under DSS contract number XAQ91-00054-(022) /A as a result of a non-solicited proposal to IMD.

Many cases have been observed where ships were unable to proceed or maneuver effectively in ice covered waters due to the onset of the lateral ice pressure. While ice pressure has long been recognised as an important factor affecting the operation of ships in ice, relatively few data points are available to quantify its effects. Consequently, this effect is not well understood and is often neglected in field trials of icebreaking ships. Qualitative assessments of the ice pressure are often made by observing the closing of the broken track behind the ship. In most full scale trials, data collected when the channel closes quickly behind the ship is usually discarded. The Canadian Coast Guard Post Acceptance Performance Appraisal (PAPA) manual, which represents the techniques and procedures for field testing ship performance in ice and open water, does not include techniques or guidelines for ice pressure because there is insufficient information available.

In model scale this effect has been investigated by some International and Canadian tanks, with limited success, as no tank has the capability to offer clients a proven system that produces reliable results.

This report presents the findings of the investigation of a simplified method for inducing in-plane lateral pressure in the model EG/AD/S ice in the Ice Tank at the Institute for Marine Dynamics.

TABLE OF CONTENTS

1.0 INTRODUCTION

1.1 Introduction

Compression in ice fields, or in-plane pressure, is caused by wind and current acting as a driving force. The movement of ice is related to the characteristics of the driving force and the dynamic behaviour of the ice field. This situation is most severe when ships become stuck in a compressive ice field in which significant moves against the ship's hull. The loads imposed on a ship's hull are developed due to crushing, buckling and bending of the moving ice against the hull plating or against deformed ice near the ship. The movement of the ship and the closing of the channel around the vessel can have a significant effect on the ship-ice interaction. Many cases have been observed where ships were unable to proceed or maneuver effectively due to the onset of ice pressure and in some severe cases, hull damage has been reported due to this effect. [1][11][12]

While ice pressure has long been recognised as an important factor affecting the operation of ships in ice, relatively few data points are available to quantify its effects and a number of factors are still unknown about this phenomena. Consequently, this effect is not well understood and is often neglected in field trials of icebreaking ships. Qualitative assessments of the ice pressure are often made by observing the closing of the broken track behind the ship. In full scale trials, data collected when the channel closes quickly behind the ship is usually discarded. The PAPA manual, which represents the latest techniques and procedures for field testing ship performance in ice and open water, does not include techniques or guidelines for ice pressure because there is insufficient information available.

In-plane pressure clearly affects the operation of icebreaking ships and the interpretation of ship trials results. [10] However, to date, it has not been explicitly included in any mathematical model for predicting ice breaking resistance, nor in any standard procedures for ship trials or model tests. Instead, the occurrence and severity of the ice pressure is typically logged qualitatively with reference to the degree of closing of the ship's track. Clearly, these observations are insufficient to provide a reliable index of the ice pressure severity. The closing of the channel is affected by both the magnitude of the pressure and by the size of the ice sheet (which affects the amount of stored strain energy). Consequently, the vessel may experience large ice pressures without significant closure of the broken track for narrow ice sheets. Thus, the traditional method of observation and documentation of in-plane pressure by reference to the degree of track closure could be misleading at best, and perhaps even meaningless, unless the floe size is also documented.

A better understanding of the phenomenon of in-plane pressure will lead to an improved general assessment of icebreaker performance, and reduce variability in the results of ship ice performance trials. This can best be achieved through physical modelling under controlled conditions of pressure and frictional resistance.

1.2 Background

A number of techniques have been developed and used in the past to simulate in-plane ice pressure in the model basin. The success of these techniques was limited by the lack of data and knowledge available concerning the process in full scale. Early physical modelling techniques developed to simulate in-plane pressures consisted of the installation of an apparatus that would provide a uniform pressure along the ice tank wall(s). Other techniques were also developed and used by a number of other laboratories around the world including HSVA in Germany, in the early 1970's, the Arctic and Antarctic Institute, the USSR in 1984 and more recently by the Ship Research Institute in Tokyo, Japan. Most of the existing systems consist of a rigid, movable side wall that pressurizes the ice sheet with varying controls on the pressure (force) and the rate of penetration (closing).

A literature search of the subject was conducted, however there was little published data found relevant to this series of tests. Abstracts of the papers that were of some relevance are presented in Appendix A.

Some in-plane pressure experiments were carried out by Fleet Technology Limited in 1977, whereby a simplified system was designed and used for in-plane pressure tests carried out on an icebreaking vessel. This system consisted of a number of push bar segments joined together with a flexible bar and loaded with weights. Figure 1.1 [2] The technique was developed to provide a system that simulated an in-plane pressure 25%, 50% and 75% of the buckling pressure of the ice sheet. Despite the large applied pressure, the increase in the total resistance achieved during the tests, for the highest pressure, was less than 50% of the total resistance of the vessel in the zero pressure ice sheets. It was believed that such high in-plane pressure would result in a much higher increase of the measured resistance of the model. The main problem of the system was that the ice was developing a shear line, which resulted in the failure of the ice on the hull of the model thus releasing the pressure. The connection of the segments together with a flexible bar was unsuccessful. It resulted in the transfer of the pressure (force) following the channel breaking from the back segments to the front ones, thus resulting in the collapse of the whole ice sheet. The problems were thought to be caused by a number of simplifications made during the simulation, ie. the in-plane pressure was applied on the model from one side only and the pressure applied did not simulate the actual strain expected to be released in full scale when a channel is broken up.

A joint research project between Helsinki University of Technology/ Laboratory of Naval Architecture and Marine Engineering, and the Academy of Sciences in the USSR/ Institute for Problems in Mechanics was conducted in June 1990 in the ice tank at the Helsinki University of Technology (HUT) to study the problems concerning ships in compressive ice.[1] A separate transverse towing line was constructed across one end of the tank, the ice field sawn into 10 m breadth ice fields and pushed against the towed model by the carriage. The model was a 1:33.5 tanker instrumented to measure model speed, towing force and compressive force at midships. Compressive force was determined by attaching a hinged plate on the port side only, and the forces at the upper end were measured with a force gauge at the fore and aft end of the plate. Figure 1.2 The process reported was concerned with compressive forces of the ice on the parallel midbody of the ship model. These tests were preliminary in nature and a number of unsolved questions arose. For example, the motions of the model and ice field were not measured; also the tests were conducted with a vertical sided ship, and since the process was "strongly" dependent on the inclination angle of the ship's side, parametric studies were recommended. The process started with ice crushing, and the forces developed finally caused the ice to fail. These problems were attributed to the "unknown physical phenomenon " in the process.

2.0 In-Plane Pressure Tube Instrument used for this Study

Drawings for the in-plane pressure apparatus reported here is presented in Figures 2.1 through 2.7. It consisted of two units approximately twelve meters (40.0 feet) in length on each side of the tank, each housing a 100mm (4 inch) diameter pneumatic hose. (Figure 2.1) Each unit, complete with hardware, weighed approximately 400 pounds thus preventing the instrument from floating up during operation.

Each "pressure tube" comprised two aluminum channels, one inside the other. A 6" x 3 1/2" x 3/8" channel was used for the 'outside housing' of the tube, while a 5" x 21/2" x 1/4" channel was used for the 'inside housing' (Figure 2.2 and 2.3). The inside of the lower flange of the outside housing was machined to give a smooth surface perpendicular to the web. 1/8" Ultra High Molecular Weight (UHMW) bearing surfaces, 4" in width were attached to the inside of the lower flange to reduce the friction between the two aluminum surfaces. Arrangements were provided to prevent the inside housing from extending completely out of the instrument. Carpet was rivetted to the outside face of the inside housing to provide an excellent bond between the instrument and the model ice sheet.

Four hangers per unit were bolted to the outside housing and were constructed such that the units could be suspended from the 'carriage rail alignment water tray' running along the top of the tank wall (Figure 2.4). Lifting holes were drilled in the hanger reinforcing bracket to facilitate hoisting the complete unit up to the 'cat walks' above the tank. (Figure 2.7) The units were stored in this location until immediately after seeding an ice sheet, when each unit was lowered into position and the block and tackle was removed. The ice sheet was allowed to grow around the unit.

A pneumatic reinforced rubber hose, 100 mm (4 inches) in diameter was sandwiched between the two aluminum channels (Figure 2.5). Both ends of this hose were capped off, with one end fitted for a standard shop pneumatic line. Compressed air, which was fed to the system from the main pneumatic supply in the tank, passed through a splitter and was diverted to each pressure tube on either side of the tank. A ball valve in the splitter manually regulated the desired pressure while a pressure gauge in the splitter indicated the maximum pressure in the units. For the second ice sheet a pressure regulator was placed in line ahead of the splitter for better control and a more constant pressure during the tests.

3.0 MODEL TESTS

3.1 Model Set-up

The model used for these tests was a 1:20 scale of the R-Class, which was constructed of a fibreglass hull coated with IMRON paint, internal plywood frames and with no superstructure fitted. The model was built to the moulded lines as given in Burrard Dry Dock Co. Ltd., drawing number 221-H-140 and fitted with a centerline rudder and ice knife. (Figure 3.1 through 3.4). No propellers were fitted, however dummy hubs and cones were fitted. Principal particulars and hydrostatic particulars for the hull are presented in Tables 3.1 through 3.4.

The model was outfitted for towed resistance tests only having the tow post at the centre of buoyancy and was restrained in surge, sway and yaw with two grasshoppers, one forward and one aft. Since model motions were not measured it was ballasted to give the correct draft and trim only. The model was ballasted to 0.347 m draft, giving a displacement of 956.9 kg., fresh water, which corresponded to 6.94 meters draft and a displacement of 7820.0 tonnes full scale.

3.2 Tank Set-up

Two ice sheets were used for these tests. Both sheets were 80mm in thickness and had a target strength of 30 kPa. The measured ice properties are presented in Appendix B.

For the first ice sheet, the first 32 meters were level unbroken ice and had normal pinning constraints, while the ice sheet between 32 and 49 meters was cut 0.5 m from the wall on both sides of the tank. The ice from these channels was completely removed. The 'pressure tube' was installed between 49m and 62m on both sides of the tank. Transverse saw cuts in the ice, isolated the sheet in way of the pressure tube instrument.

For the second ice sheet, the first 32 meters had normal pinning constraints, with a pre-sawn pattern between 0m and 16m and level unbroken ice between 16m and 32 meters. The ice sheet between 32 and 49 meters was cut 0.5 m from the wall on both sides of the tank and again the ice from these channels was completely removed. The 'pressure tube' was again installed between 49m and 62m on both sides of the tank and the sheet isolated in this region.

The tank set-up for both tests is presented in Figure 3.4.

3.3 Model Tests

Two model speeds of 0.115 m/s and 0.23 m/s, corresponding to 1.0 and 2.0 knots, full scale, were run for each of the three ice conditions for each ice sheet. All tests were conducted in the centre channel. The following tests were performed:

Level Ice Resistance Tests: These tests model an infinite ice sheet and were conducted at one target strength and thickness for both ice sheets, with run lengths of approximately twice the model length. The data was labelled NORMAL for these tests.

Presawn Ice Resistance Tests: These tests were carried out at the same two speeds and run lengths as for the level ice resistance tests and were conducted in the second sheet only, since both ice sheets were similar in thickness and target conditions. This data was labelled PRE-SAWN and was used for analysis of the data from both ice sheets (See Section 4.1).

The location of the quarter and side cuts for the pre-sawn pattern were determined from the following formula:

$$b/2 = (Beam_{max}/2) + (1.5 * t)$$

where 'b/2' was the half width of the presawn channel, '$Beam_{max}$' was the maximum width of the model at the waterline and 't' was the nominal ice thickness. Another longitudinal cut 'b prime' was sawn on both sides of the channel at a location of 60%*(b/2) and measured from the centerline of the model. Wishbone saw cuts were made at angles approximately 60 degrees and 0.25 meters in length along this channel.

Level Ice Resistance Tests in a Finite Sheet: Following the pre-sawn and normal level ice resistance tests, a slot approximately 0.5m in width and 17m in length was cut along the side of the tank. All the ice was removed from the slot. The centre portion of the ice sheet in this region was left intact. This data was labelled FREE for these tests.

Pressured Level Ice Resistance Tests: For each sheet the pressure tube was installed at locations between 49 and 62 meters. To minimise creep in the pressurised region of the ice, the model was stopped at the tank 48 meter mark, and the pressure tube activated. The model was then run in the centre channel. This data was labelled PRESSURED for these tests.

Model speed, position and tow post resistance were measured for all tests.

4.0 ANALYSIS

4.1 Resistance Analysis

For all speeds and ice cases, except the second speed in the Pressured Resistance tests (0.23 m/s), the statistics of the time series plots were selected at the last one half model length per model speed, to avoid areas affected by ice sheet property measurements. This allowed at least one model length for the data to reach steady state. However, for the 0.23 m/s in the pressured ice, it was observed that at the end of the run, the resistance started to decrease. It was felt that this was in part due to the pressure tub extending to its maximum at the leading edge, and thus the pressure in the system was reduced at this stage since the volume in the feed airlines was not sufficient to keep up with the expansion demand. Hence, for this case and speed, the time histories just prior to the decreasing resistance were selected. Time history plots for each run are presented in Appendix C.

The resistance data was corrected to target conditions as follows:

For the target strength and speed, the presawn resistance(Ris) from the second day of tests, was subtracted from each measured total resistance (Rit) to yield the breaking ice resistance (Rib), Eq. [1.]

$$Rib(\sigma_m, h_m) = Rit(\sigma_m, h_m) - Ris \qquad [1]$$

where σ_m and h_m are the ice strength and thickness, respectively, as measured at test time. $Rib(\sigma_m, h_m)$ was then corrected for the target strength as per Eq. [2.]

$$Rib(\sigma_t, h_m) = Rib(\sigma_m, h_m) * \sigma_t/\sigma_m \qquad [2]$$

where σ_t is the target strength. Since only one ice thickness was used for both tests 'n' could not be determined using Eq. 3. as is normal practice, but was selected to be equal to 2 for this analysis.

$$Rib(\sigma_t, h_m) = ah^n \qquad [3]$$

$Rib(\sigma_t, h_m)$ was then corrected for the target thickness as per Eq. 4.

$$Rib(\sigma_t, h_t) = Rib(\sigma_t, h_m) * (h_t/h_m)^n \qquad [4]$$

where h_t is the target ice thickness. The presawn resistance data, $Ris(\sigma_m, h_t)$ was then corrected for thickness only, as per Eq. 5.

$$Ris(\sigma_m, h_t) = Ris(\sigma_m, h_m) * (h_t/h_m) \qquad [5]$$

The total model resistance, corrected for the target strength and thickness was then found as per Eq. 6.

$$Rit(\sigma_t, h_t) = Rib(\sigma_t, h_t) + Ris(\sigma_m, h_t) \qquad [6]$$

Tables 4.1 and 4.2 present the measured data for each run and ice sheet, respectively. Tables 4.3 and 4.4, and Figure 4.1 presents this data corrected to target conditions

For comparison only, the forces and pressures exerted over the forward region of the hull, as a result of the induced in-plane pressure were estimated as follows, under the following simple assumptions:

- The forward region of the hull was continually in contact with the ice sheet,
- The ice sheet was continually under a uniform in-plane compressive pressure in a direction perpendicular to the motion of the model
- The major influence of the pressure tube instrument was on the "breaking component" of the measured resistance.

The forward region of the hull, from the stem to approximately the maximum beam (station 12), and extending 80mm below the test waterline was discretized into segments. The length, l_i and width, w_i of each segment were defined by:

$$l_i = LBP / (40 * \cos\alpha_i) \quad [7]$$

$$w_i = h / \cos\beta_i \quad [8]$$

where, LBP is the Length Between Perpendiculars, h is the ice thickness and α_i is the average waterline angle, and β_i is the flare angle for each panel. The force on each segment was defined by:

$$F_i = p * (LBP/40) * h \quad [9]$$

where p is the estimated in-plane pressure applied by the instrument. The normal force on each segment was calculated from Equation 10 :

$$F_{in} = F_i * \cos\alpha_i * \cos\beta_i \quad [10]$$

The forces in the x, y and z directions were then calculated as follows:

$$F_{ix} = F_{in} * \sin\alpha_i * \cos\beta_i \quad [11]$$
$$F_{iy} = F_{in} * \cos\alpha_i * \cos\beta_i \quad [12]$$
$$F_{iz} = F_{in} * \sin\beta_i \quad [13]$$

The resulting equivalent pressures were calculated from Equation 14.

$$P_{(x,y,z)} = \Sigma F_{i(x,y,z)} / \Sigma (l_i * w_i) \quad [14]$$

The breaking resistance in the 'NORMAL' ice tests were corrected to the equivalent conditions in the 'PRESSURED' ice tests as per Equation 15:

$$Rib(\sigma_t, h_m) = Rib(\sigma_m, h_m) * (\sigma_t + P_x)/\sigma_m \quad [15]$$

The breaking resistance in the 'PRESSURED' ice tests were corrected to the equivalent conditions in the 'NORMAL' ice tests as per Equation 16:

$$Rib(\sigma_t, h_m) = Rib(\sigma_m, h_m) * \sigma_t/(\sigma_m + P_x) \quad [16]$$

A summary of the data is presented in Table 4.5

4.2 Observations

During the first day of testing, it was difficult to hold a constant pressure in the instrument, since the tubes were expanding and stopping as it applied pressure to the ice. At times more pressure was induced than desired, since the ball valve was much too sensitive for the desired application. As a result, it was observed, and confirmed by the videos, that the ice sheet experienced some buckling, with a lowering of the sheet within 1.0 meter off the pressure tube, on both sides of the tank. Some water was observed on the ice in this region. When the pressure in the tube was allowed to drop slightly, this effect was reduced. However, after the tests, the ice in this region was examined and it was noted that there was a crack in the ice running along the length of the tube in this region. This may have caused a premature relief of pressure.

The pressure tube instrument had a maximum restricted extension of 75 mm (approx. 3 inches) per tube, a maximum of 150mm (6 inches) overall. The ice was frozen to the carpet on the outer face of the instrument and bonded well. The ice thickness was 80mm (3.15 inches), and the broken channel was observed to be approximately 114 - 125 mm (4.5 - 5.0 inches), per side, wider than the model. Therefore it is anticipated that little or no pressure was induced in the model along the parallel middle body, since no ice floes were observed trapped between the sheet and the model and the associated measured increase in resistance was a function of the "breaking component" of the model resistance only.

During the running of the model through the pressure region, particularly for the higher speed, the tube extended to maximum. Since the in-plane pressure housing was then not perpendicular to the tank sides, and the contact area between the pneumatic hose and the pressure housing was reduced to minimum, it was felt that the results were not valid after this occurred. During the analysis, when the last model length for this region was selected, the results were somewhat lower, and it appeared that the pressure had been relieved in the ice at that stage, thus the results presented in this report (Section 4.1) are from the stats prior to this occurring. Even though the results indicate an increase in resistance, it is anticipated that it is somewhat reduced for the amount of in-plane pressure induced.

5.0 DISCUSSION OF RESULTS.

A summary of the resistance data analysis for each sheet and each ice condition, corrected to the target strength of 30 kPa and 80 mm thickness is presented in Table 5.1. There was approximately an average decrease of 5.3% and 16.8% in the total resistance, and 7.2% and 22.5% for the breaking resistance for each speed, respectively from the NORMAL to the FREE condition, and an approximate average increase of 14.6% and 8.8% in the total resistance, and 19.8% and 11.7% for the breaking resistance for each speed, respectively from the NORMAL to the PRESSURED condition.

Comparisons of the results from the NORMAL and PRESSURED cases, estimated as per Equations 15 and 16, indicate that possibly the major influence of the in-plane pressure induced during these tests was on the breaking component of resistance since there is a reasonably good agreement between the measured and calculated corrected data. From observations during testing, and confirmed by the videos of the tests, this is borne out, since the instrument did not extend sufficiently nor fast enough to compress the ice sheet or broken floes against the model sides. This would indicate that the instrument, as tested, would be effective with a restriction on the ice thickness. Since the instrument has a maximum extension of approximately 75 mm, it is estimated that the maximum ice sheet thickness to be tested effectively would be approximately 65 mm. Also, as the air supply was configured, the rate of extension was insufficient for the thicker ice sheet.

According to reference [13], it was concluded that the width of the channel between the hull and the tank wall had little significant effect on the measured resistance, provided that it was greater than 2.5 lengths of the model width. This applies to tests in an infinite sheet. During these tests with the ice edge removed from the tank wall at a distance of 0.5m per side, the sheet was of a finite width. No separation of the ice channel, nor transverse cracks were observed during runs. One explanation of the reduction in resistance between the NORMAL and the FREE test case is that as the sheet was grown and tempered, it attempted to expand, and thus there was compressive strength, or in-plane stress built-up in the ice. This stress was released when the sides were relieved from the wall, thus producing a lower resistance measurement.

6.0 CONCLUSIONS

From the experience gained with the instrument set-up and installation in the tank, this method of applying an in-plane pressure in a model ice sheet could be viable, with restrictions on the thickness of ice sheets and improvements in the volume of air supplied.

From observation and the videos recorded, the pressure device performed as anticipated, with no freeze ups or sticking.

From Figure 5.1, it appears that there was indeed an increase in the towed resistance of the model as it passed through the different ice conditions - free, normal and pressured. However, the scatter in the data prevents absolute conclusion on wether the results are reliable, and to what extent.

From the videos and the analysis, it appears that the increase in total resistance reported here is a result of the influence of the in-plane pressure on the breaking component only, with little or no influence on the submergence and clearing component, nor on the increased resistance due to the ice sheet being compressed against the model's sides.

7.0 RECOMMENDATIONS

Based on the tests performed, the results presented here and the experience gained with this instrument, the following recommendations are proposed:

1. Additional testing, including; the measurement of ice strain (transverse deflection) at all three condition locations; in-plane pressures in the ice at regular intervals particularly in way of the 'pressured' tests; install a calibrated grid in the overhead videos of the bow and side pieces; and for varying the thickness of ice.

2. Consider provisions for increasing the travel length (extension) of the instrument.

3. Provisions could be made to ensure more control over the instrument pressure.

4. Provisions could be made to allow for an increased flow rate of air and a regulator installed in each unit to maintain a more constant pressure in the tube.

5. In an attempt to reduce buckling, particularly for thinner ice sheets, consider the option of installing the instrument closer to the model track.

8.0 REFERENCES

1. Kujala, P., Goldstein, R., Osipenko,N., Danilenko, V., June 1991, " A Ship in Compressive Ice- Preliminary model test results and analysis of the process", Helsinki University of Technology, Facility of Mechanical Engineering Laboratory of Naval Architecture and Marine Engineering, Otaniemi 1991/M-111

2. Edwards, R.Y., Abdelnour, A., Nawwar, A., October 1978, "Testing Program for Developing Hull Shapes for Icebreaking LNG Ships", Fleet Technology Report FR340C-6

3. Kerr, A.D., August 1978, "On the Determination of Horizontal Forces a Floating Plate Exerts on a Structure", U.S. Army Cold Regions Research and Engineering Laboratory, CRREL Report # CR 78-15

4. Vivatrat, V., Chen,V., Bruen, F.J., November 1984, "Ice Load Prediction for Arctic Nearshore Zone", Cold Regions Science and Technology, Vol. 10, No. 3, p 75-87

5. Takeuchi, T., et al, June 1989, "Deformation of Floating Ice Sheets of Variable Thickness Under In-Plane Compressive Loading", International Conference on Port and Ocean Engineering under Arctic Conditions, Proceedings POAC 89, Vol 1., p 385-407

6. Timco, G.W., Frederking, R., April 1983, "Confined Compressive Strength of Sea Ice", Seventh International Conference on Port and Ocean Engineering under Arctic Conditions, Proceedings POAC 83, Vol 1., p 243-253

7. Blanchet, D. et al, Hamza, H., April 1983, "Plane Strain Compressive Strength of First Year Beaufort Sea Ice", Seventh International Conference on Port and Ocean Engineering under Arctic Conditions, Proceedings POAC 83, Vol 3., p 84-96

8. Haynes, F.D., Sodhi, D.S. , April 1983, " Ice Forces on Model Marine Structures", Seventh International Conference on Port and Ocean Engineering under Arctic Conditions, Proceedings POAC 83, Vol 2., p 778-787

9. Tsutae, S., Itoh, Y., Izumi, K, Ono, T., Saeki, H., April 1983, " Estimation of the Compressive Strength of Sea Ice by the Schmidt Test Hammer", Seventh International Conference on Port and Ocean Engineering under Arctic Conditions, Proceedings POAC 83, Vol 2., p 1080-1089

10. Howard, D., Abdelnour, R., et al, December 1987, " The Testing of the 1:8 Scale Model of the R-Class in Level Ice", Transportation Development Centre, TP 8828E

11. Bykow, V., September 1984, "Quand L'Artique Se Fache", Spoutnik digest de la Presse Societique

12. Barr, W., Wilson, E., et al, 1985, "The Shipping Crisis in the Soviet Eastern Arctic at the Close of the 1983 Navigation Season", Arctic, Vol 38, No. 1, p 1-17

13. Bulat,V., Glen, I.F., August 1981, "The Testing of a Ship Model in Ice for the National Research Council", Final Report, Arctec Canada Limited, FR 335C-4

LIST OF FIGURES

FIGURE [illegible] 1

INPLANE PRESSURE MODEL TESTING
AFTER NAWWAR ET AL['2]

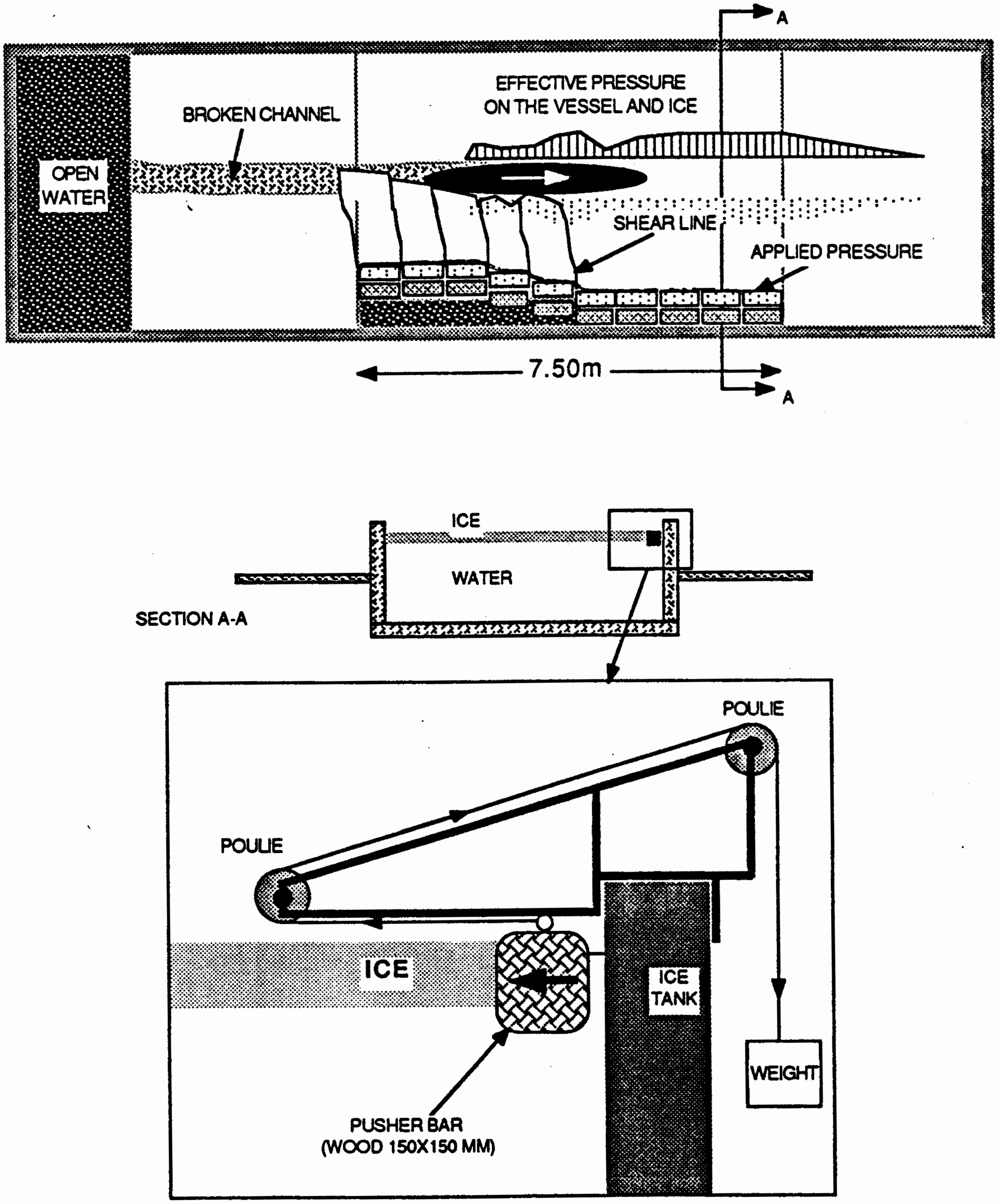
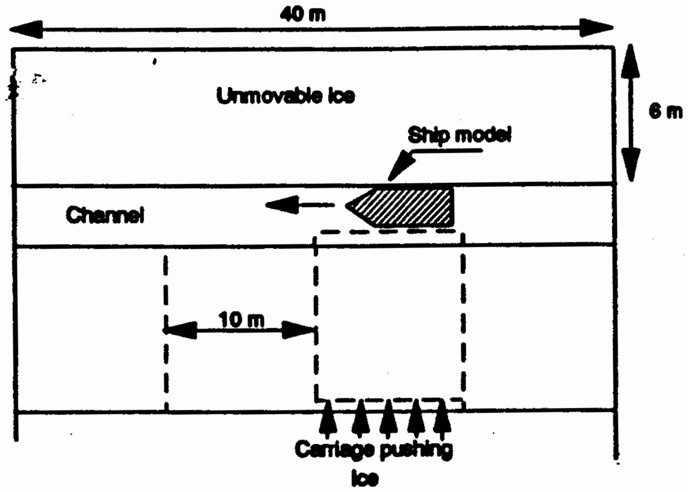
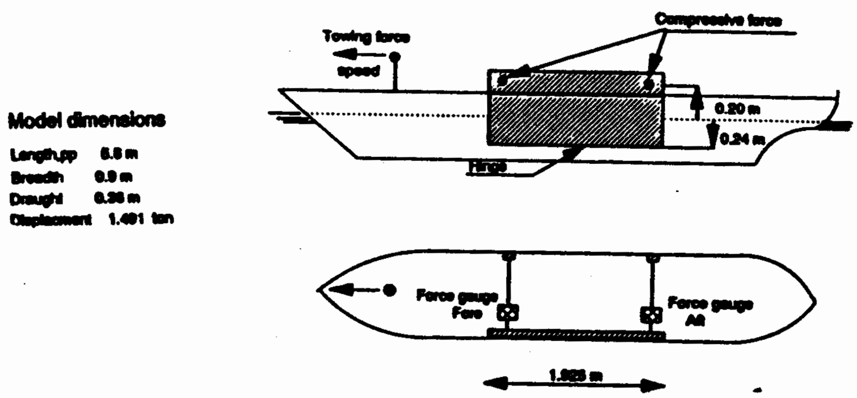


Figure 1.2
Inplane Pressure Model Testing after Kujala



Layout of the test arrangements in the ice tank.



The instrumentation and main dimensions of the model

Figure 2.1

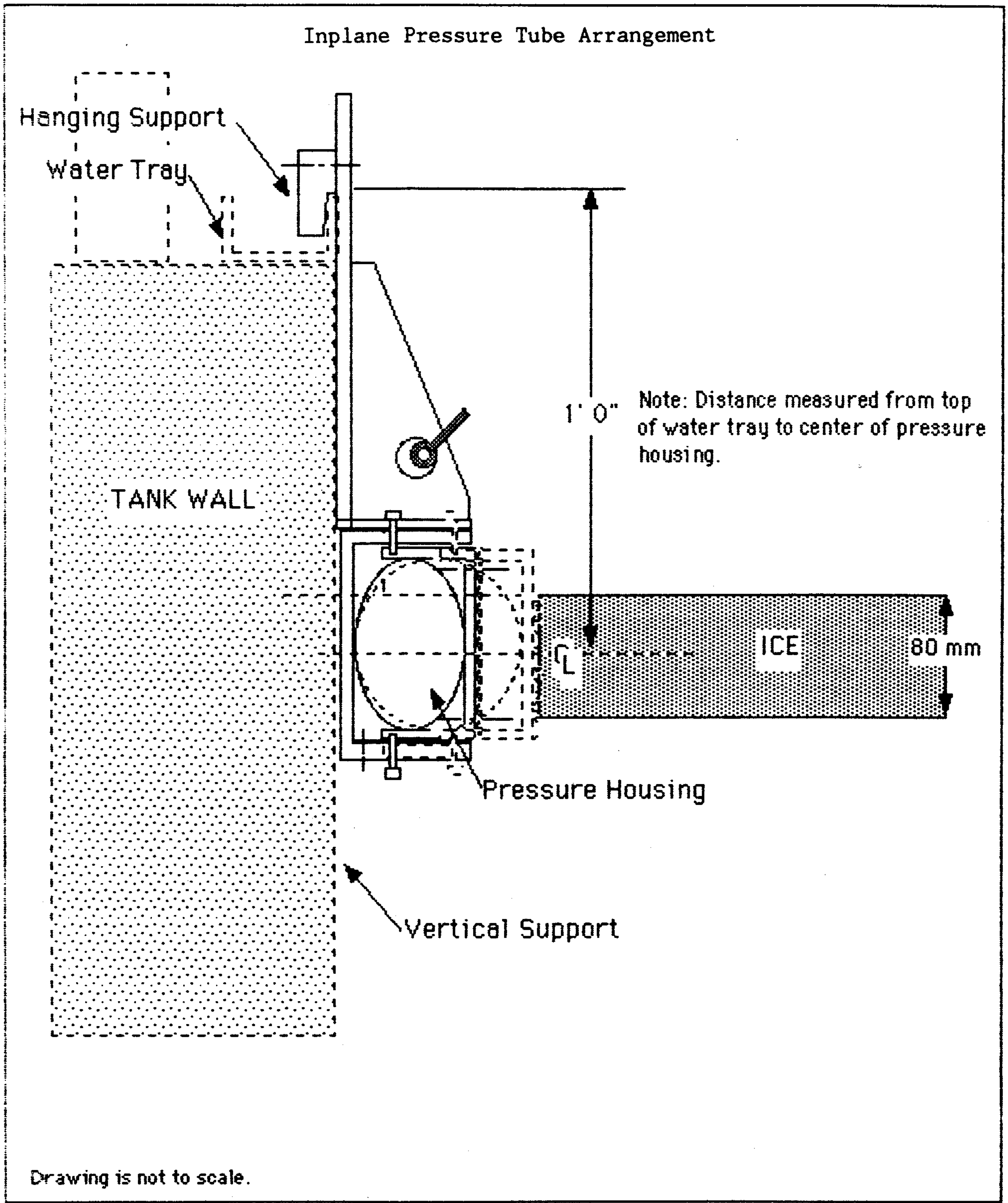

Inplane Pressure Tube Arrangement
Hanging Support
Water Tray
1' 0"
Note: Distance measured from top of water tray to center of pressure housing.
TANK WALL
ICE
80 mm
Pressure Housing
Vertical Support
Drawing is not to scale.

Figure 2.2

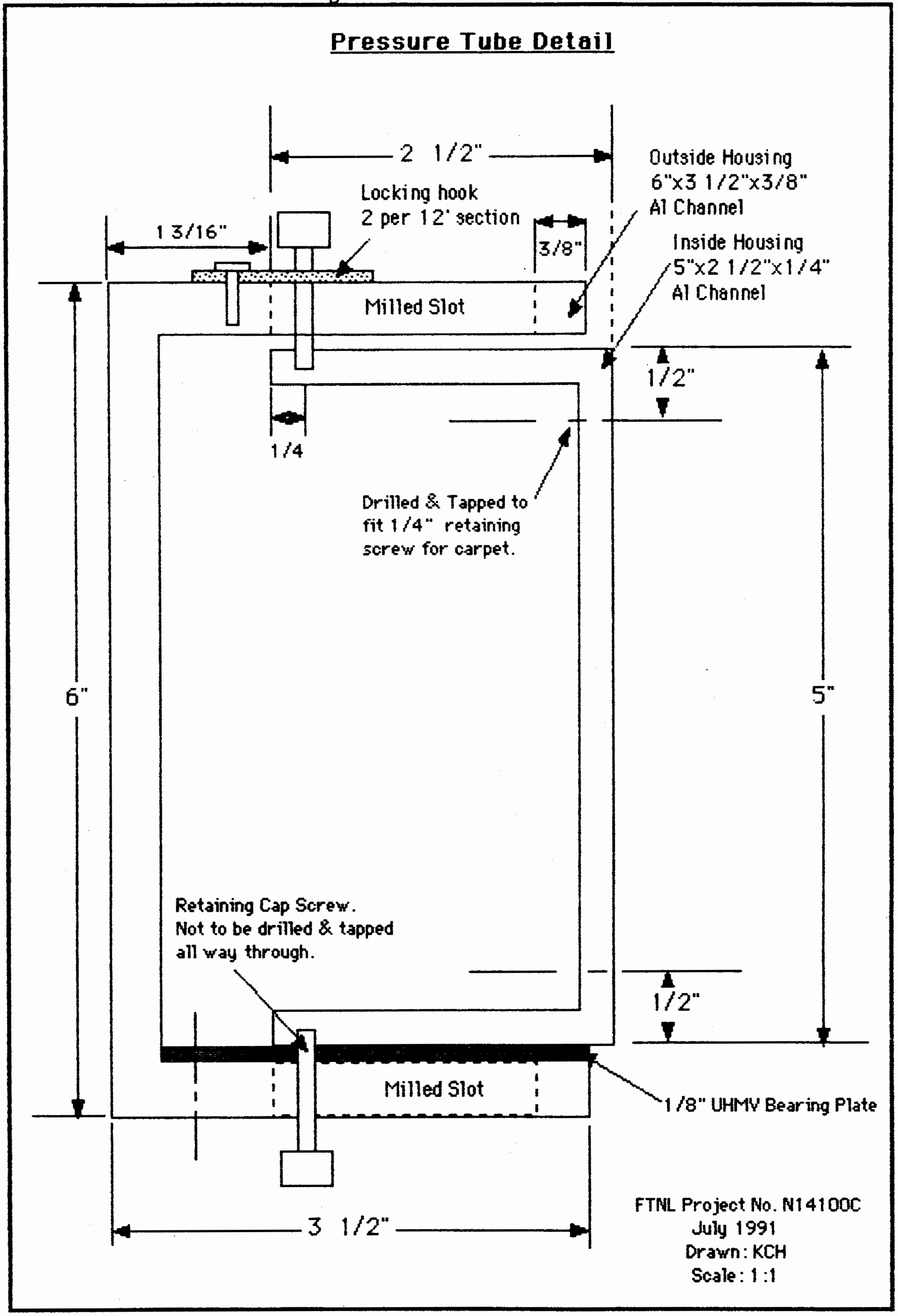
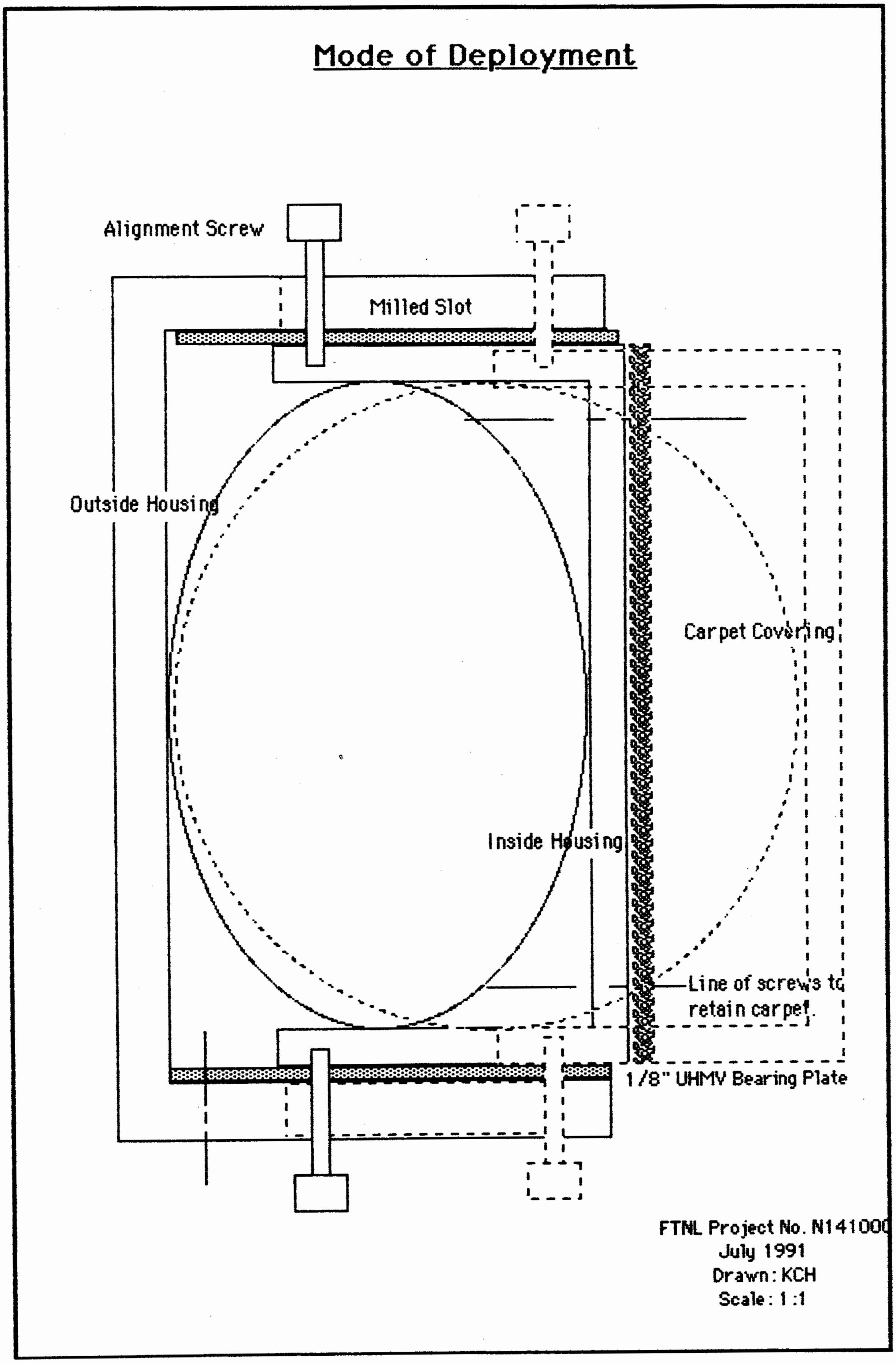
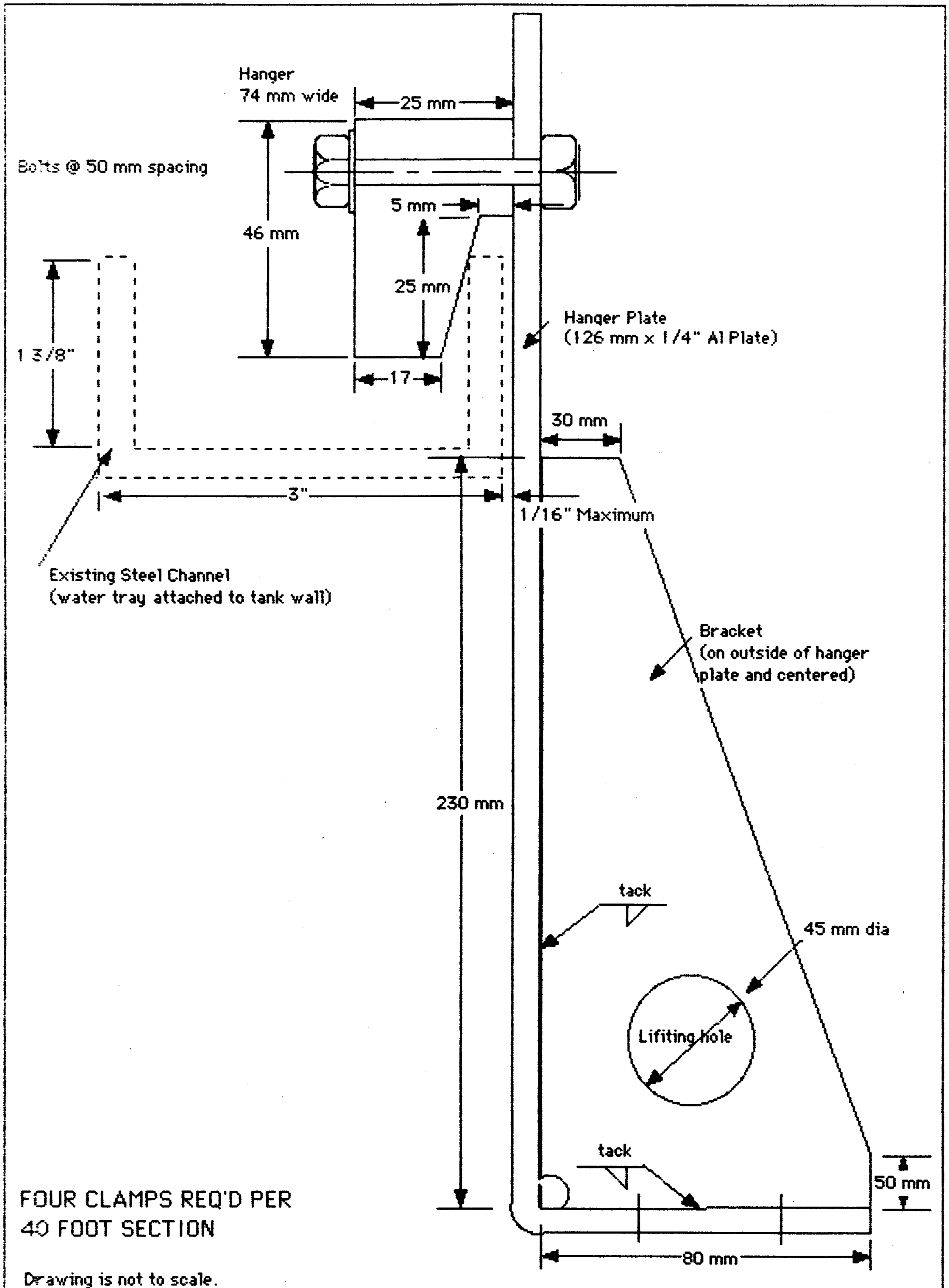

Pressure Tube Detail
2 1/2"
Outside Housing
6"x3 1/2"x3/8"
Al Channel
Locking hook
2 per 12' section
1 3/16"
3/8"
Inside Housing
5"x2 1/2"x1/4"
Al Channel
Milled Slot
1/2"
1/4
Drilled & Tapped to
fit 1/4" retaining
screw for carpet.
6"
5"
Retaining Cap Screw.
Not to be drilled & tapped
all way through.
1/2"
Milled Slot
1/8" UHMV Bearing Plate
3 1/2"
FTNL Project No. N14100C
July 1991
Drawn: KCH
Scale: 1:1

Figure 2.3



Mode of Deployment
Alignment Screw
Milled Slot
Outside Housing
Carpet Covering
Inside Housing
Line of screws to
retain carpet.
1/8" UHMV Bearing Plate
FTNL Project No. N141000
July 1991
Drawn: KCH
Scale: 1:1

Figure 2.4


Hanger
74 mm wide
25 mm
Bolts @ 50 mm spacing
46 mm
5 mm
25 mm
Hanger Plate
(126 mm x 1/4" Al Plate)
17
1 3/8"
30 mm
3"
1/16" Maximum
Existing Steel Channel
(water tray attached to tank wall)
Bracket
(on outside of hanger
plate and centered)
230 mm
tack
45 mm dia
Lifiting hole
tack
50 mm
80 mm
FOUR CLAMPS REQ'D PER
40 FOOT SECTION
Drawing is not to scale.

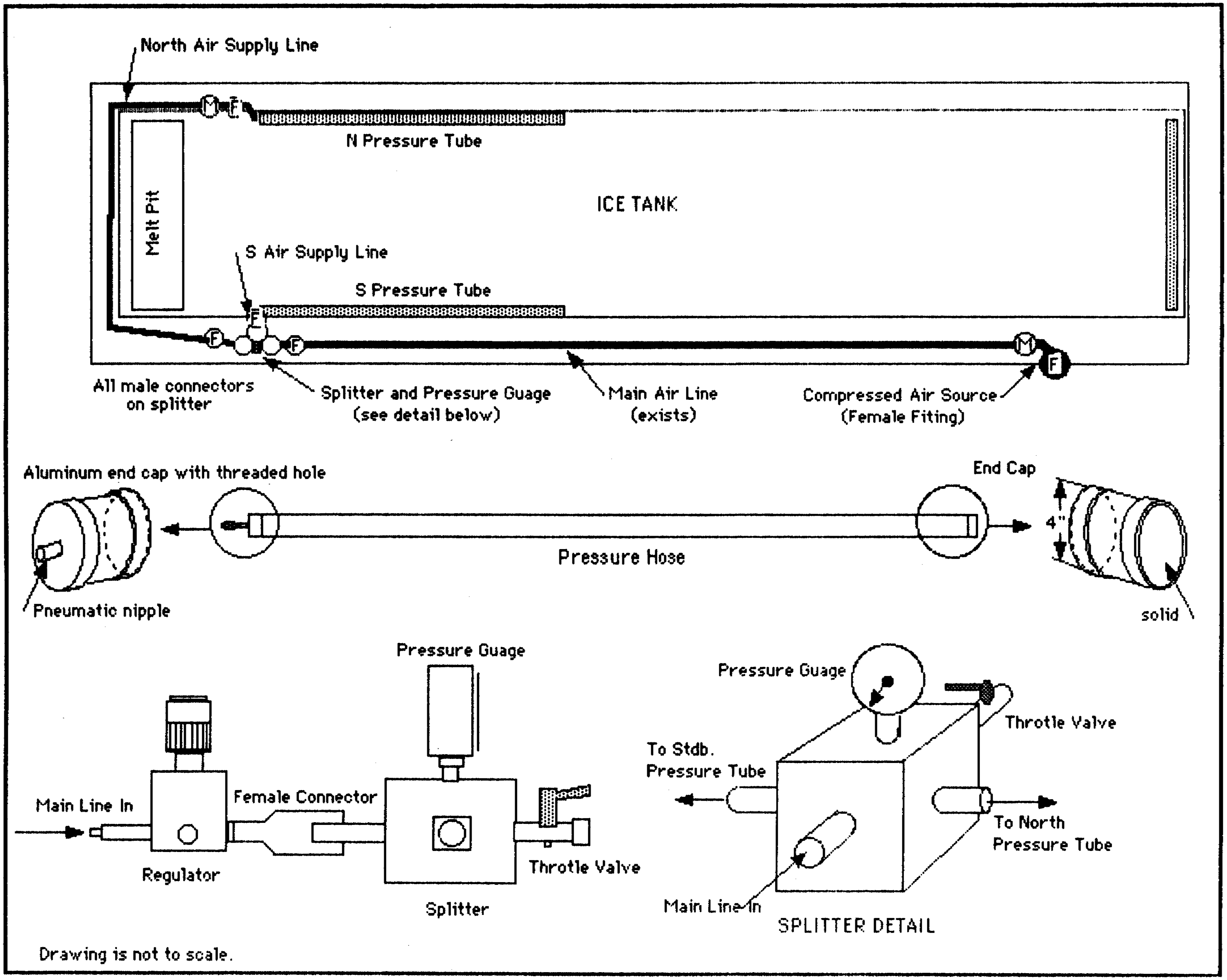
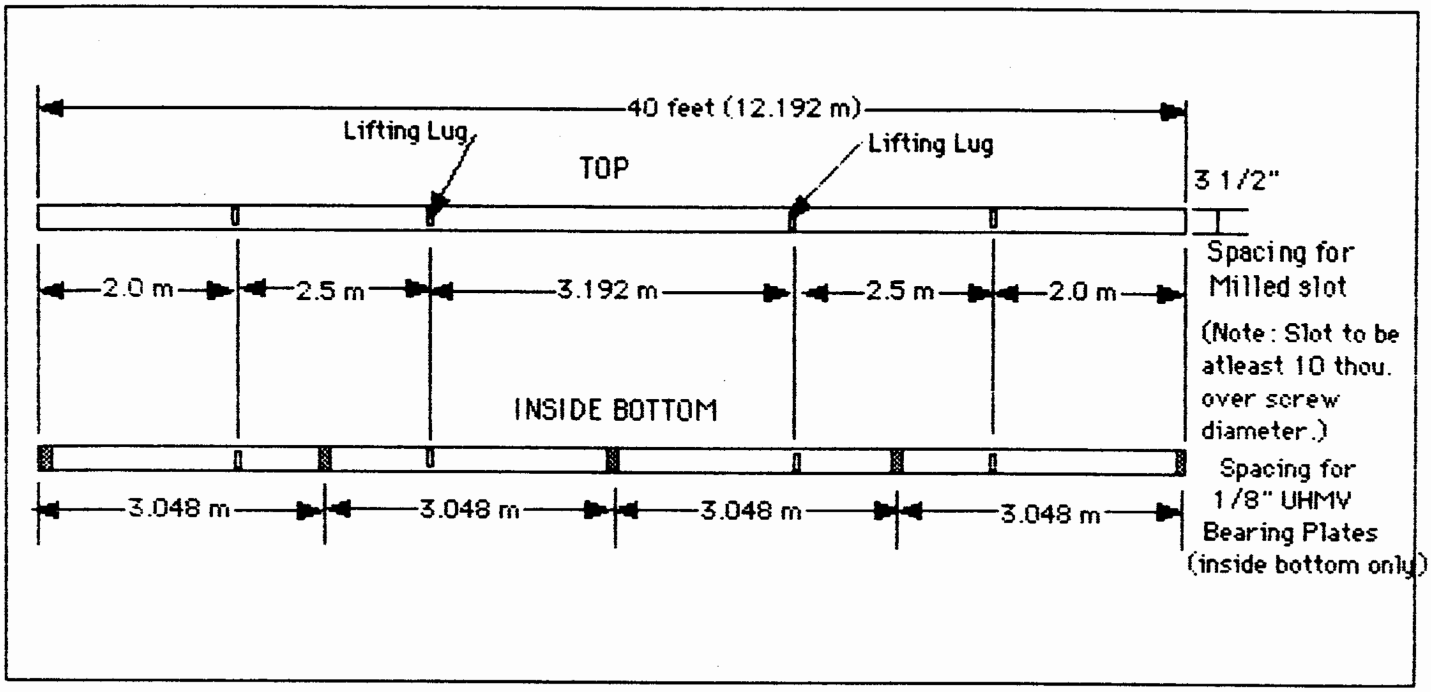

North Air Supply Line
M
F
N Pressure Tube
ICE TANK
Melt Pit
S Air Supply Line
S Pressure Tube
F
All male connectors
on splitter
Splitter and Pressure Guage
(see detail below)
Main Air Line
(exists)
Compressed Air Source
(Female Fiting)
Aluminum end cap with threaded hole
End Cap
4"
Pressure Hose
Pneumatic nipple
solid
Pressure Guage
Pressure Guage
Throtle Valve
To Stdb.
Pressure Tube
Main Line In
Female Connector
To North
Pressure Tube
Regulator
Throtle Valve
Splitter
Main Line In
SPLITTER DETAIL
Drawing is not to scale.

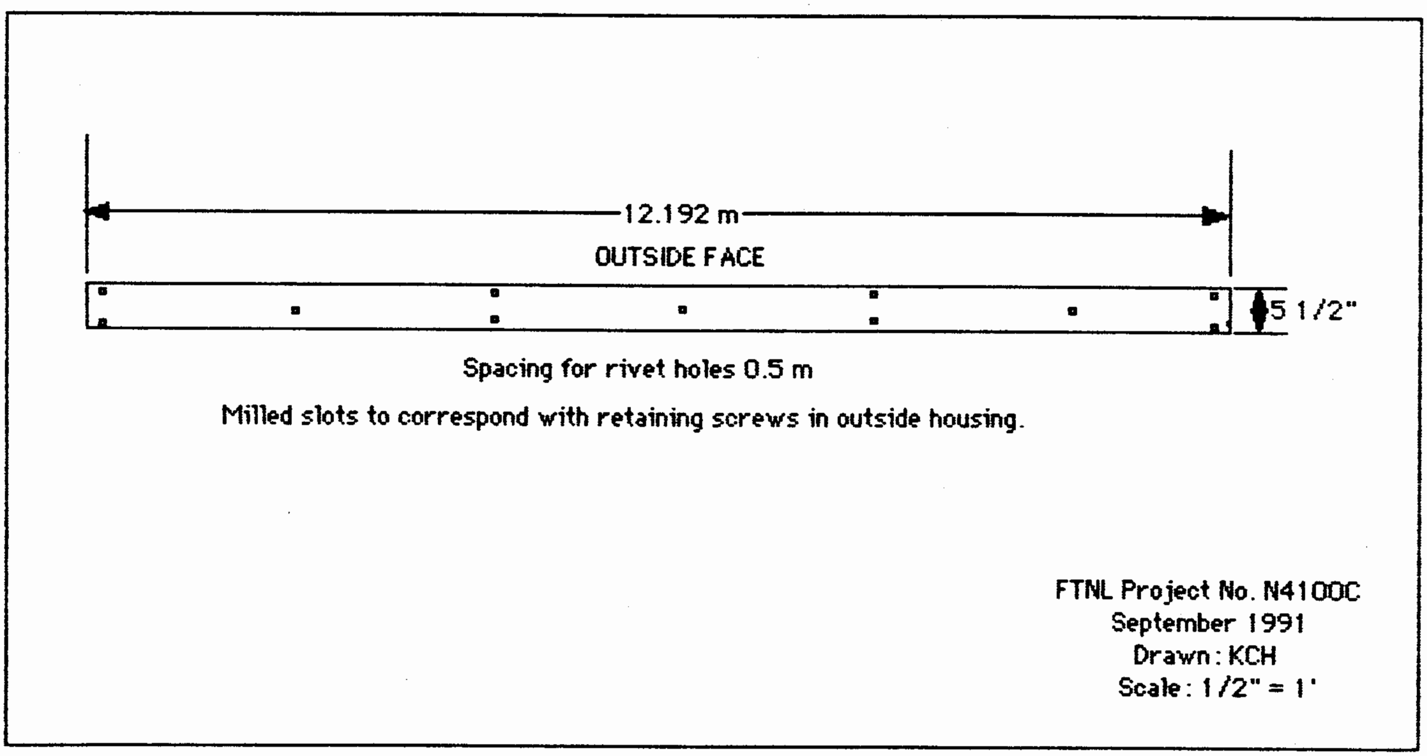
Figure 2.5

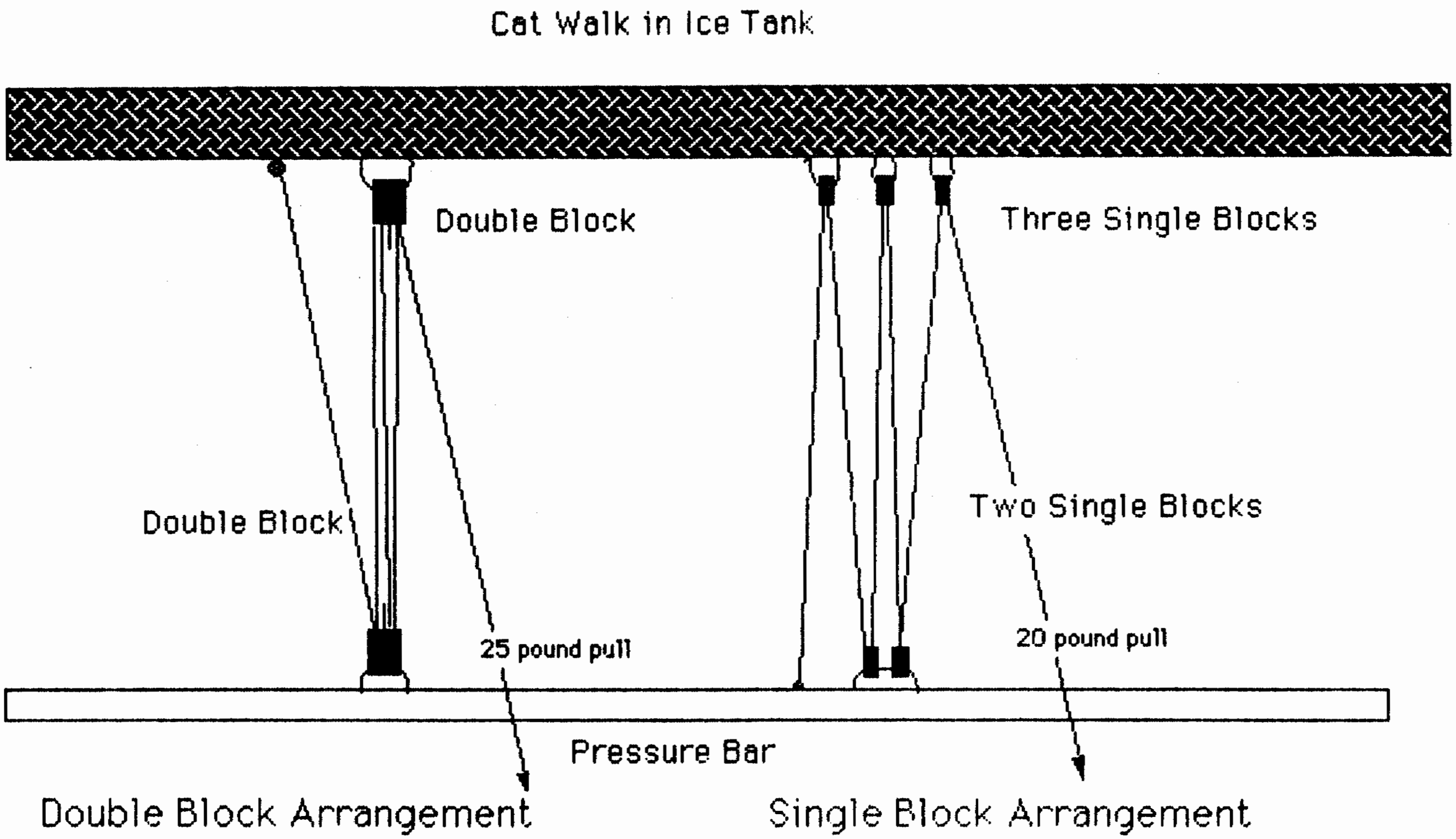
Figure 2.6

PRESSURE TUBE - OUTSIDE HOUSING



PRESSURE TUBE - INSIDE HOUSING





Inventory 8 locations

12 Double blocks, 12 large shackles, 6 small shackles - 6 locations
10 Single blocks, 2 large shackles, 2 small shackles, 6 medium shackles - 2 locations

Figure 2.7

Figure 5.1

MODEL 327

BODY PLAN

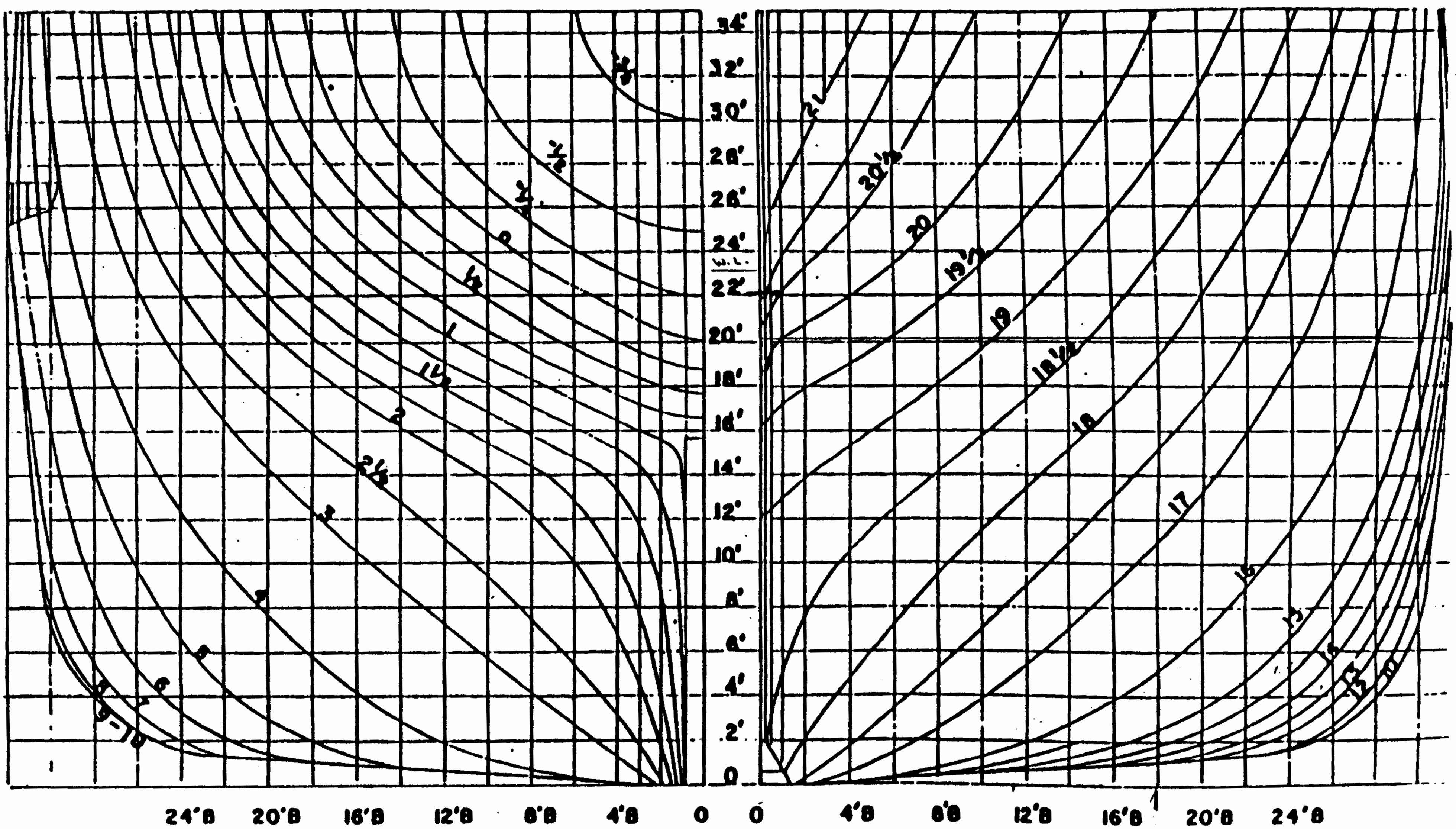


Figure 3.2

BOW AND STERN LINES
MODEL 327

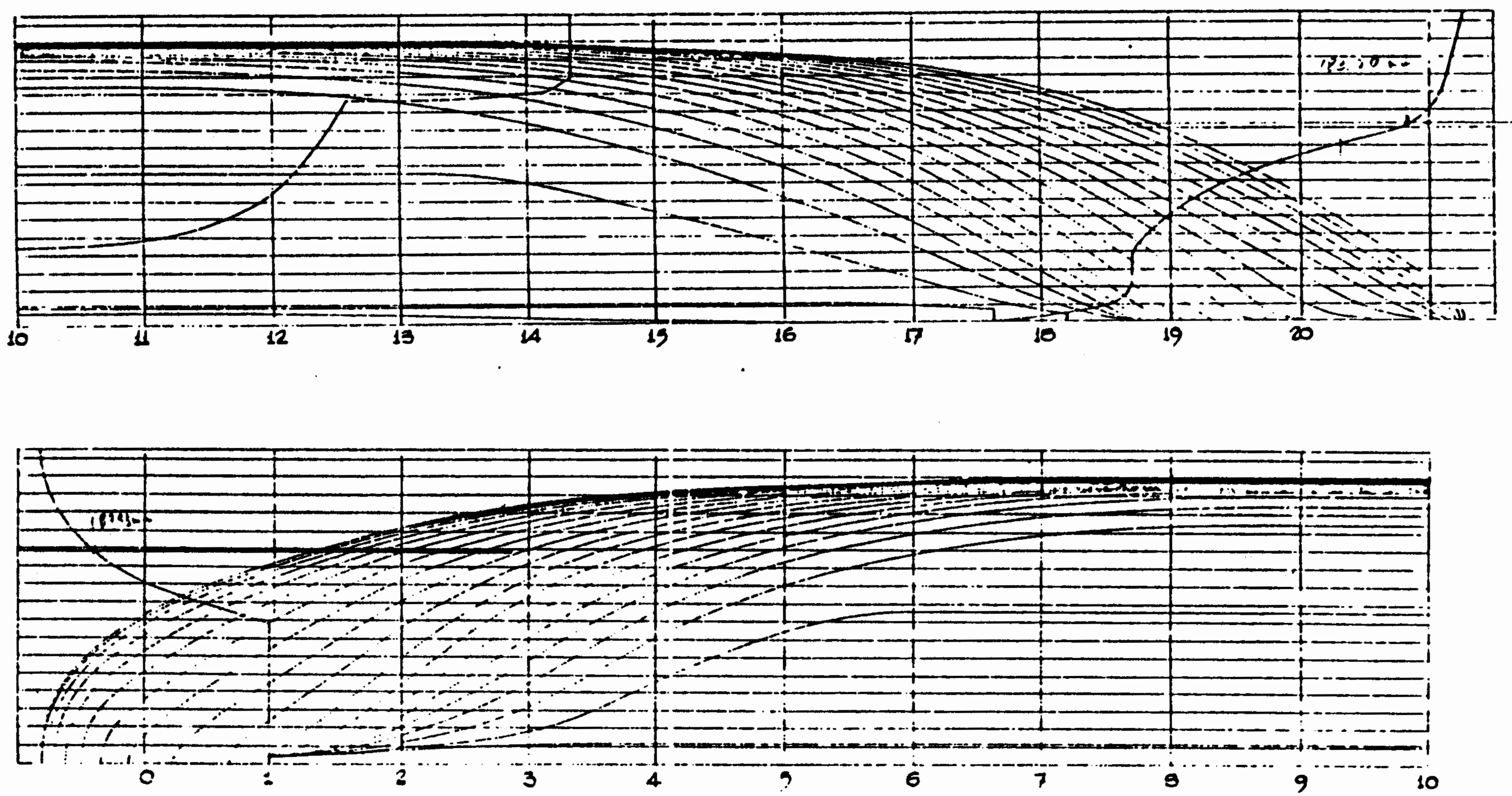
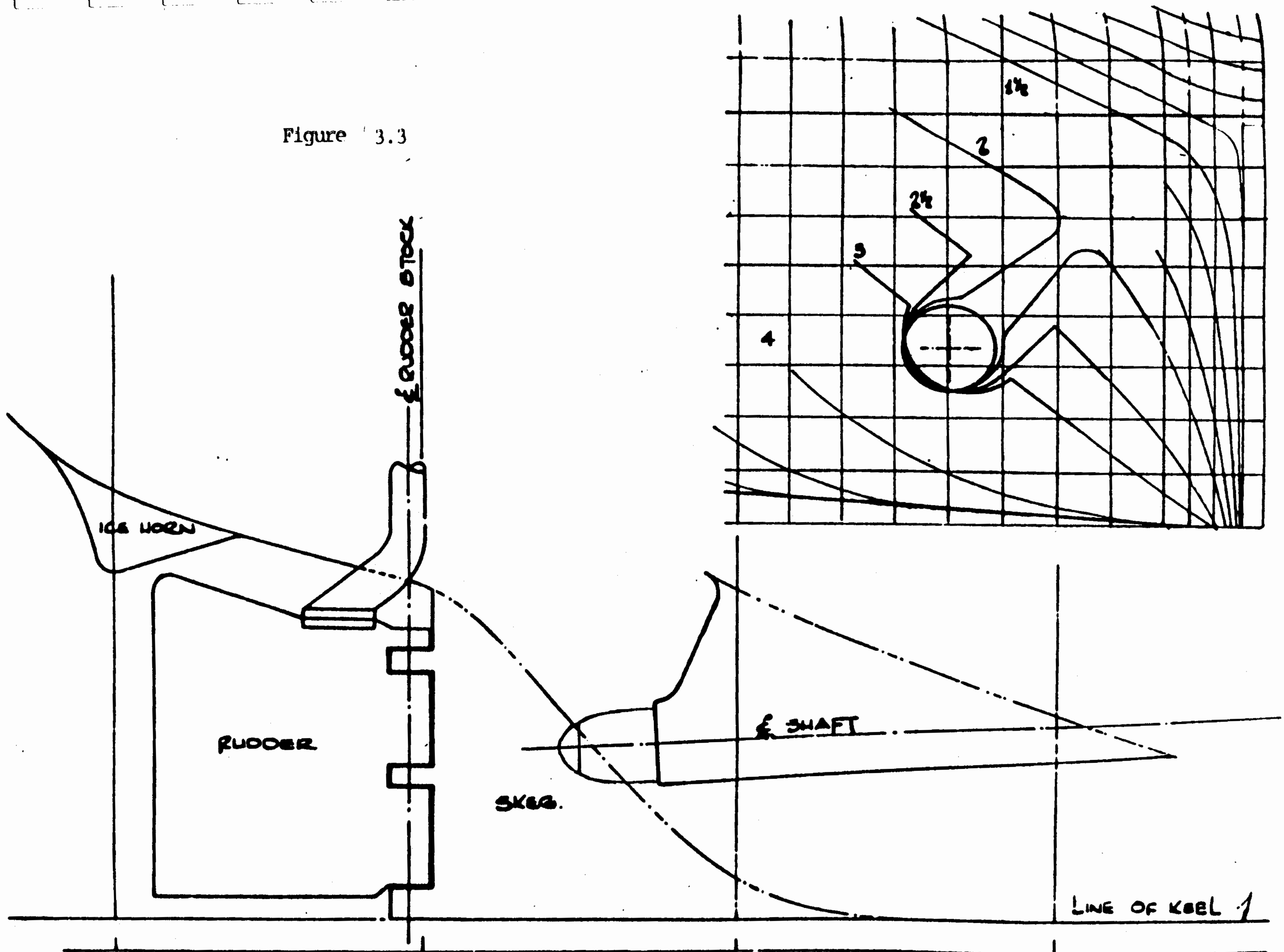


Figure 3.3



M-327 STERN ARRGT

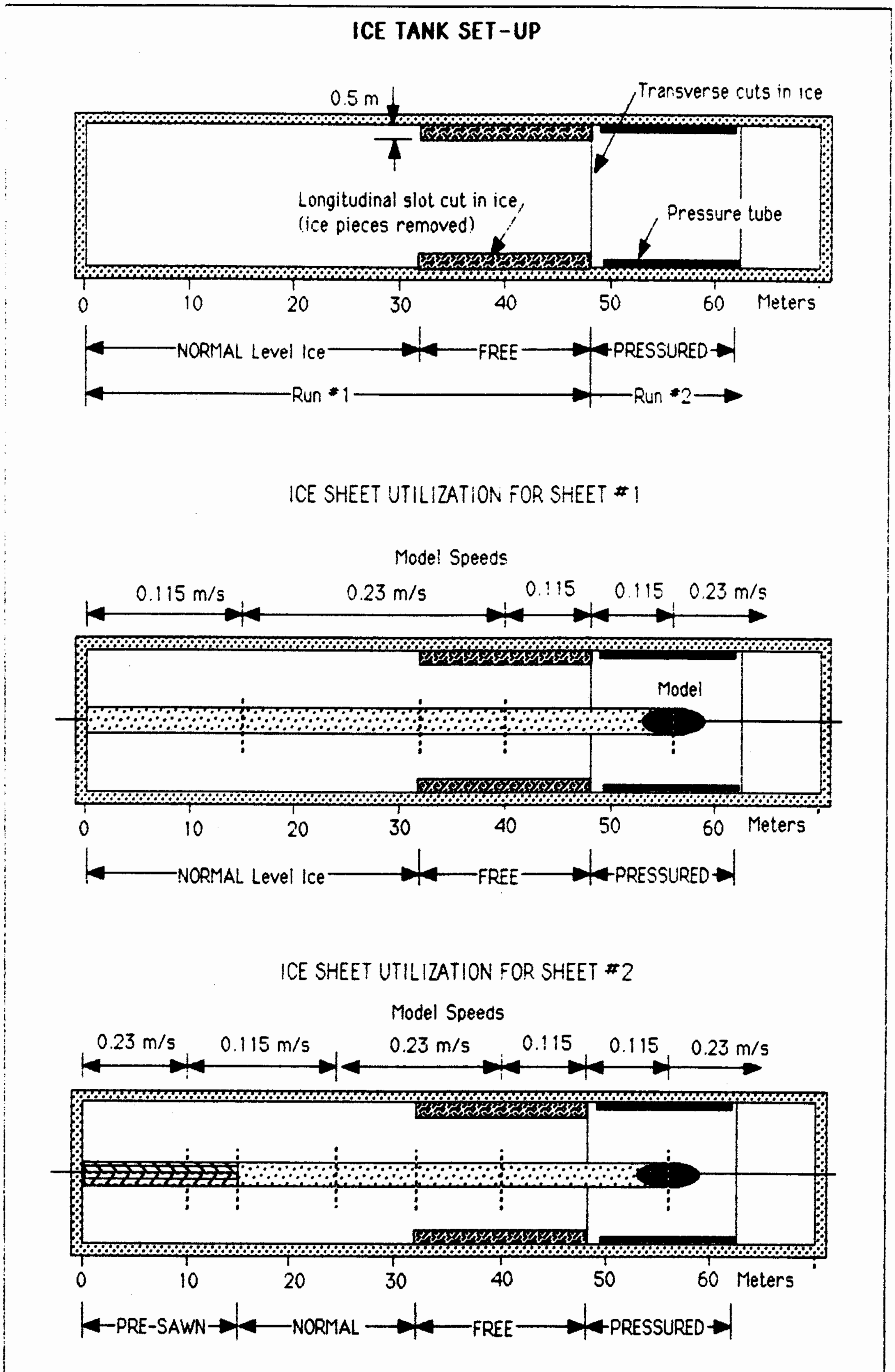

ICE TANK SET-UP
0.5 m
Transverse cuts in ice
Longitudinal slot cut in ice
(ice pieces removed)
Pressure tube
0
10
20
30
40
50
60
Meters
NORMAL Level Ice
FREE
PRESSURED
Run #1
Run #2
ICE SHEET UTILIZATION FOR SHEET #1
Model Speeds
0.115 m/s
0.23 m/s
0.115
0.115
0.23 m/s
Model
0
10
20
30
40
50
60
Meters
NORMAL Level Ice
FREE
PRESSURED
ICE SHEET UTILIZATION FOR SHEET #2
Model Speeds
0.23 m/s
0.115 m/s
0.23 m/s
0.115
0.115
0.23 m/s
0
10
20
30
40
50
60
Meters
PRE-SAWN
NORMAL
FREE
PRESSURED

Figure 3.4

Figure 4.1a

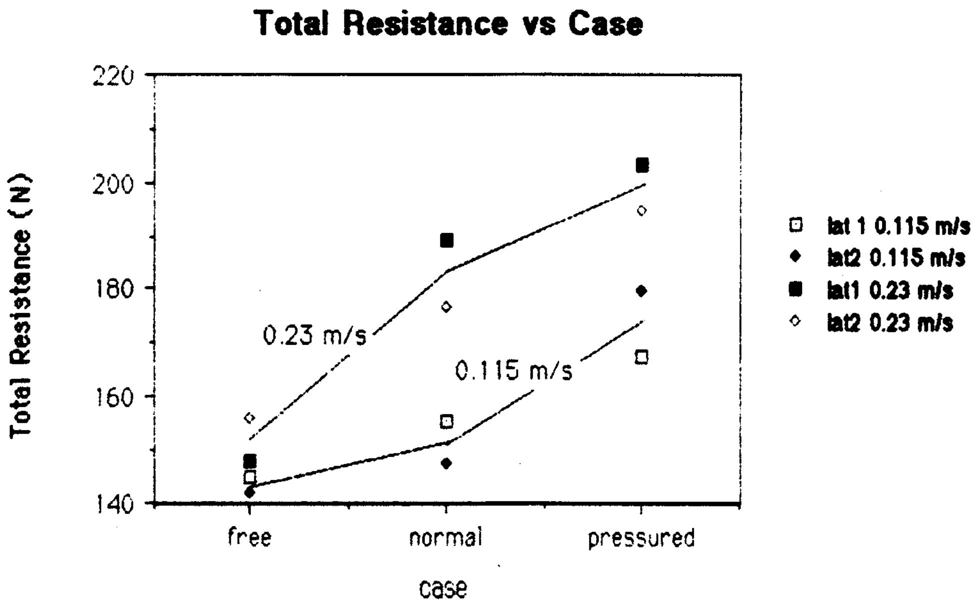
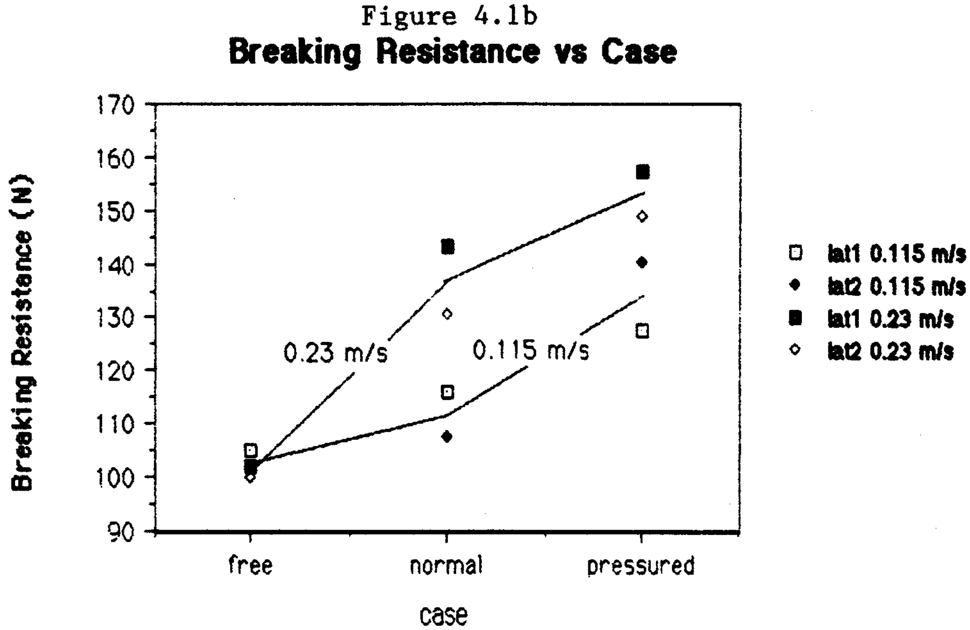


Figure 4.1b



LIST OF TABLES

Table 3.1

MODEL 327
R-CLASS ICE BREAKER
ITTC TEST DRAFTS

HYDROSTATIC PARTICULARS FOR MODEL OF SCALE 1/20 WITHOUT APPENDAGES

LENGTH BETWEEN PERPENDICULARS (LPP), M	4.397
LENGTH ON WATERLINE (LWL), M	4.650
WATERLINE BEAM AT MIDSHIPS, M	0.968
WATERLINE BEAM AT MAXIMUM SECTION, M	0.968
MAXIMUM WATERLINE BEAM, M	0.969
DRAFT AT MIDSHIPS, M	0.347
DRAFT AT MAXIMUM SECTION, M	0.349
DRAFT AT AFT PERPENDICULAR, M	0.358
DRAFT AT FORWARD PERPENDICULAR, M	0.335
EQUIVALENT LEVEL KEEL DRAFT, M	0.347
MAXIMUM SECTION FORWARD OF MIDSHIPS, M	-0.370
PARALLEL MIDDLE BODY, FROM, AFT OF MIDSHIPS, M	0.370
TO, FORWARD OF MIDSHIPS, M	-0.370
AREA OF MAXIMUM STATION, SQ. M	0.309
CENTER OF BUOYANCY FORWARD OF MIDSHIPS (LCB), M	0.016
CENTER OF BUOYANCY ABOVE KEEL, M	0.194
WETTED SURFACE AREA, SQ. M	5.339
VOLUME OF DISPLACEMENT, CU. M	0.954
DISPLACEMENT, KG OF FRESH WATER	953.7
CENTER OF FLOATATION FORWARD OF MIDSHIPS (LCF), M	-0.035
CENTER OF FLOATATION ABOVE KEEL, M	0.347
AREA OF WATERLINE PLANE, SQ. M	3.598
TRANSVERSE METACENTRIC RADIUS (BM), M	0.244
LONGITUDINAL METACENTRIC RADIUS (BML), M	4.800
CENTER OF AREA OF PROFILE PLANE FORWARD OF MIDSHIPS (CLR), M	-0.039
CENTER OF AREA OF PROFILE PLANE ABOVE KEEL, M	0.179
AREA OF PROFILE PLANE, SQ. M	1.405

INCLUDING BOSSINGS, ICE HORN AND RUDDER

VOLUME OF DISPLACEMENT, CU. M	0.957
DISPLACEMENT, KG OF FRESH WATER	956.9
CENTER OF BUOYANCY FORWARD OF MIDSHIPS	-0.023

Table 3.2

MODEL 327
R-CLASS ICEBREAKER
ITTC TEST DRAFTS

HYDROSTATIC PARTICULARS FOR A FULL SIZED SHIP WITHOUT APPENDAGES

LENGTH BETWEEN PERPENDICULARS (LPP), M	87.93
LENGTH ON WATERLINE (LWL), M	93.00
WATERLINE BEAM AT MIDSHIPS, M	19.36
WATERLINE BEAM AT MAXIMUM SECTION, M	19.36
MAXIMUM WATERLINE BEAM, M	19.37
DRAFT AT MIDSHIPS, M	6.93
DRAFT AT MAXIMUM SECTION, M	6.97
DRAFT AT AFT PERPENDICULAR, M	7.16
DRAFT AT FORWARD PERPENDICULAR, M	6.71
EQUIVALENT LEVEL KEEL DRAFT, M	6.94
MAXIMUM SECTION FORWARD OF MIDSHIPS, M	-7.39
PARALLEL MIDDLE BODY, FROM, AFT OF MIDSHIPS, M	7.39
TO, FORWARD OF MIDSHIPS, M	-7.39
AREA OF MAXIMUM STATION, SQ. M	123.41
CENTER OF BUOYANCY FORWARD OF MIDSHIPS (LCB), M	-0.33
CENTER OF BUOYANCY ABOVE KEEL, M	3.88
WETTED SURFACE AREA, SQ. M	2135.52
VOLUME OF DISPLACEMENT, CU. M	7629.27
DISPLACEMENT, TONNES OF SALT WATER	7820.00
CENTER OF FLOATATION FORWARD OF MIDSHIPS (LCF), M	-0.69
CENTER OF FLOATATION ABOVE KEEL, M	6.94
AREA OF WATERLINE PLANE, SQ. M	1439.10
TRANSVERSE METACENTRIC RADIUS (BM), M	4.89
LONGITUDINAL METACENTRIC RADIUS (BML), M	96.00
CENTER OF AREA OF PROFILE PLANE FORWARD OF MIDSHIPS (CLR), M	-0.77
CENTER OF AREA OF PROFILE PLANE ABOVE KEEL, M	3.57
AREA OF PROFILE PLANE, SQ. M	562.05

Table).3

MODEL 327
R-CLASS ICE BREAKER
ITTC TEST DRAFTS

COEFFICIENTS OF FORM FOR NAKED HULL

COEFFICIENTS BASED ON: LENGTH ON WATERLINE
MAXIMUM BEAM
EQUIVALENT LEVEL KEEL DRAFT

L/B	4.802
L/T	13.407
B/T	2.792
LCB %L FORWARD OF MIDSHIPS	-0.355
LCF %L FORWARD OF MIDSHIPS	-0.743
CLR %L FORWARD OF MISHIPS	-0.832
CB	0.611
CMAX	0.918
CP	0.665
CW	0.799
CIX	0.662
CIY	0.564
BM/B	0.252
BML/L	1.032
KB/T	0.560
BEAM - DISPLACEMENT RATIO (CIRCB)	0.984
DRAFT - DISPLACEMENT RATIO (CIRCT)	0.352
LENGTH - DISPLACEMENT RATIO (CIRCM)	4.724
WETTED SURFACE - DISPLACEMENT RATIO (CIRCS)	5.510
BM - DISPLACEMENT RATIO	0.248
BML - DISPLACEMENT RATIO	4.876
AREA OF PROFILE PLANE/LT	0.871

Table 3.4

MODEL 327
R-CLASS ICE BREAKER
ITTC TEST DRAFTS

SUMMARY OF NORMALIZED STATION DATA

STATION	AREA	BEAM	DEPTH
0	0.023	0.246	0.146
1	0.132	0.518	0.767
2	0.341	0.709	0.997
3	0.567	0.830	0.994
4	0.759	0.903	0.991
5	0.880	0.948	0.987
6	0.948	0.980	0.984
7	0.987	0.998	0.981
8	0.999	1.000	0.978
9	0.999	1.000	0.975
10	0.995	0.999	0.971
11	0.990	0.999	0.968
12	0.981	0.999	0.965
13	0.960	0.997	0.962
14	0.919	0.988	0.959
15	0.848	0.961	0.955
16	0.736	0.904	0.952
17	0.565	0.801	0.949
18	0.331	0.632	0.921
19	0.097	0.399	0.422
20	0.008	0.127	0.131

AFT END OF WATERLINE IS AT -0.395
FORWARD END OF WATERLINE IS AT 20.758

AREA IS STATION AREA / MAXIMUM SECTION AREA
BEAM IS STATION BEAM / MAXIMUM WATERLINE BEAM
DEPTH IS STATION DEPTH / MAXIMUM DRAFT

Table 4.1

PRESSURISED ICE RESISTANCE ANALYSIS **MEASURED DATA**

Model Name: R-CLASS
Model Scale: 20
Target Strength (kPa): 30
Target Thickness (mm): 80
Estimated Inplane Pressure #1: 59
Estimated Inplane Pressure #2: 118
Estimated inplane pressure x component speed 1 (kPa): 2.918
Estimated inplane pressure x component speed 2 (kPa): 5.835

	ICE PROPERTIES							RESISTANCE DATA		
	TARGET		**MEASURED**					Uncorrected		
TEST NAME	σ	ht	σ	hml	hms	n	Vmodel	Rit	Ris	Rib
	(kPa)	(mm)	(kPa)	(mm)	(mm)		(m/s)	(N)	(N)	(N)
Standard Analysis										
LATERAL1-NORMAL	30	80	37	78.3	80.0	2.00	0.115	176.9	39.7	137.1
LATERAL1-NORMAL	30	80	37	79.0	80.3	2.00	0.230	218.6	46.4	172.3
Case Converted to Pressured Tests Conditions										
LATERAL1-NORMAL	30	80	37	78.3	80.0	2.00	0.115	176.9	39.7	137.1
LATERAL1-NORMAL	30	80	37	79.0	80.3	2.00	0.230	218.6	46.4	172.3

Target Strength (kPa): 30
Target Thickness (mm): 80

	ICE PROPERTIES							RESISTANCE DATA		
	TARGET		**MEASURED**					Uncorrected		
TEST NAME	σ	ht	σ	hml	hms	n	Vmodel	Rit	Ris	Rib
	(kPa)	(mm)	(kPa)	(mm)	(mm)		(m/s)	(N)	(N)	(N)
LATERAL1-FREE	30	80	38	78.1	80.0	2.00	0.115	166.7	39.7	127.0
LATERAL1-FREE	30	80	38	75.8	80.3	2.00	0.230	162.2	46.4	115.8

Target Strength (kPa): 30
Target Thickness (mm): 80

	ICE PROPERTIES							RESISTANCE DATA		
	TARGET		**MEASURED**					Uncorrected		
TEST NAME	σ	ht	σ	hml	hms	n	Vmodel	Rit	Ris	Rib
	(kPa)	(mm)	(kPa)	(mm)	(mm)		(m/s)	(N)	(N)	(N)
Standard Analysis										
LATERAL 1-PRESS	30	80	33	79.7	80.0	2.00	0.115	179.4	39.7	139.7
LATERAL 1-PRESS	30	80	33	75.8	80.3	2.00	0.230	201.5	46.4	155.1
Case Converted to Normal Test Conditions										
LATERAL 1-PRESS	30	80	33	79.7	80.0	2.00	0.115	179.4	39.7	139.7
LATERAL 1-PRESS	30	80	33	75.8	80.3	2.00	0.230	201.5	46.4	155.1

Table 4.2

PRESSURISED ICE RESISTANCE ANALYSIS — MEASURED DATA

Model Name: R-CLASS
Model Scale: 20
Target Strength (kPa): 30
Target Thickness (mm): 80
Estimated Inplane Pressure #1: 99
Estimated Inplane Pressure #2: 89
Estimated inplane pressure x component speed 1 (kPa): 4.896
Estimated inplane pressure x component speed 2 (kPa): 4.401

	ICE PROPERTIES							RESISTANCE DATA		
	TARGET		MEASURED					Uncorrected		
TEST NAME	σ	ht	σ	hml	hms	n	Vmodel	Rit	Ris	Rib
	(kPa)	(mm)	(kPa)	(mm)	(mm)		(m/s)	(N)	(N)	(N)
Standard Analysis										
LATERAL2-NORMAL	30	80	36	82.8	80.0	2	0.115	178.2	39.7	138.5
LATERAL2-NORMAL	30	80	36	80.0	80.3	2	0.230	203.2	46.4	156.9
Case Converted to Pressured Tests Conditions										
LATERAL2-NORMAL	30	80	36	82.8	80.0	2	0.115	178.2	39.7	138.5
LATERAL2-NORMAL	30	80	36	80.0	80.3	2	0.230	203.2	46.4	156.9

Target Strength (kPa): 30
Target Thickness (mm): 80

	ICE PROPERTIES							RESISTANCE DATA		
	TARGET		MEASURED					Uncorrected		
TEST NAME	σ	ht	σ	hml	hms	n	Vmodel	Rit	Ris	Rib
	(kPa)	(mm)	(kPa)	(mm)	(mm)		(m/s)	(N)	(N)	(N)
LATERAL2-FREE	30	80	31	80.0	80.0	2	0.115	145.4	39.7	105.7
LATERAL2-FREE	30	80	31	79.5	80.3	2	0.230	158.9	46.4	112.5

Target Strength (kPa): 30
Target Thickness (mm): 80

	ICE PROPERTIES							RESISTANCE DATA		
	TARGET		MEASURED					Uncorrected		
TEST NAME	σ	ht	σ	hml	hms	n	Vmodel	Rit	Ris	Rib
	(kPa)	(mm)	(kPa)	(mm)	(mm)		(m/s)	(N)	(N)	(N)
Standard Analysis										
LATERAL 2-PRESS	30	80	30	81.4	80.0	2	0.115	184.7	39.7	145.0
LATERAL 2-PRESS	30	80	30	81.1	80.3	2	0.230	199.4	46.4	153.0
Case Converted to Normal Test Conditions										
LATERAL 2-PRESS	30	80	30	81.4	80.0	2	0.115	184.7	39.7	145.0
LATERAL 2-PRESS	30	80	30	81.1	80.3	2	0.230	199.4	46.4	153.0

Table 4.3

PRESSURISED ICE RESISTANCE ANALYSIS

Model Name: R-CLASS
Model Scale: 20

LATERAL 1-NORMAL

ICE PROPERTIES				RESISTANCE DATA						
TARGET				Corrected						
σ	ht	n	Vmodel	Rib(N)	Rib(N)	Ris(N)	Rit(N)	Rit(kN)	Vship	PE
(kPa)	(mm)		(m/s)	σ	h	h	(model)	(ship)	(k)	(kW)
Standard Analysis										
30	80	2.00	0.12	111.2	116.0	39.7	155.7	1246	1.00	641
30	80	2.00	0.23	139.7	143.2	46.2	189.4	1515	2.00	1559
Case Converted to Pressured Tests Conditions										
30	80	2.00	0.12	122.0	127.3	39.7	167.0	1336	1.00	687
30	80	2.00	0.23	166.8	171.1	46.2	217.3	1738	2.00	1788

LATERAL 1- FREE

ICE PROPERTIES				RESISTANCE DATA						
TARGET				Corrected						
σ	ht	n	Vmodel	Rib(N)	Rib(N)	Ris(N)	Rit(N)	Rit(kN)	Vship	PE
(kPa)	(mm)		(m/s)	σ	h	h	(model)	(ship)	(k)	(kW)
30	80	2.00	0.12	100.3	105.3	39.7	145.0	1160	1.00	597
30	80	2.00	0.23	91.4	102.0	46.2	148.2	1185	2.00	1219

LATERAL 1 - PRESSURED

ICE PROPERTIES				RESISTANCE DATA						
TARGET				Corrected						
σ	ht	n	Vmodel	Rib(N)	Rib(N)	Ris(N)	Rit(N)	Rit(kN)	Vship	PE
(kPa)	(mm)		(m/s)	σ	h	h	(model)	(ship)	(k)	(kW)
Standard Analysis										
30	80	2.00	0.12	127.0	127.9	39.7	167.6	1341	1.00	689
30	80	2.00	0.23	141.0	157.2	46.2	203.4	1627	2.00	1674
Case Converted to Normal Test Conditions										
30	80	2.00	0.12	116.7	117.5	39.7	157.2	1258	1.00	647
30	80	2.00	0.23	119.8	133.6	46.2	179.8	1438	2.00	1480

Table 4.4

PRESSURISED ICE RESISTANCE ANALYSIS

Model Name: R-CLASS
Model Scale: 20

LATERAL2-NORMAL

ICE PROPERTIES				RESISTANCE DATA						
TARGET				**Corrected**						
σ	ht	n	Vmodel	Rib(N)	Rib(N)	Ris(N)	Rit(N)	Rit(kN)	Vship	PE
(kPa)	(mm)		(m/s)	σ	h	h	(model)	(ship)	(k)	(kW)
Standard Analysis										
30	80	2.00	0.12	115.4	107.7	39.7	147.4	1179	1.00	607
30	80	2.00	0.23	130.7	130.7	46.2	176.9	1415	2.00	1455
Case Converted to Pressured Tests Conditions										
30	80	2.00	0.12	134.2	125.3	39.7	165.0	1320	1.00	679
30	80	2.00	0.23	149.9	149.8	46.2	196.0	1568	2.00	1613

LATERAL2-FREE

ICE PROPERTIES				RESISTANCE DATA						
TARGET				**Corrected**						
σ	ht	n	Vmodel	Rib(N)	Rib(N)	Ris(N)	Rit(N)	Rit(kN)	Vship	PE
(kPa)	(mm)		(m/s)	σ	h	h	(model)	(ship)	(k)	(kW)
30	80	2.00	0.12	102.3	102.3	39.7	142.0	1136	1.00	584
30	80	2.00	0.23	108.9	110.3	46.2	156.5	1252	2.00	1288

LATERAL2 - PRESSURED

ICE PROPERTIES				RESISTANCE DATA						
TARGET				**Corrected**						
σ	ht	n	Vmodel	Rib(N)	Rib(N)	Ris(N)	Rit(N)	Rit(kN)	Vship	PE
(kPa)	(mm)		(m/s)	σ	h	h	(model)	(ship)	(k)	(kW)
Standard Analysis										
30	80	2.00	0.12	145.0	140.1	39.7	179.8	1438	1.00	740
30	80	2.00	0.23	153.0	148.8	46.2	195.0	1560	2.00	1604
Case Converted to Normal Test Conditions										
30	80	2.00	0.12	124.6	120.4	39.7	160.1	1281	1.00	659
30	80	2.00	0.23	133.4	129.7	46.2	175.9	1407	2.00	1448

Table 4.5

Ressistance Data Corrected for Estimated In-plane Pressure

	Normal		Normal Corrected		Pressured		Pressured Corrected		
Model Speed (m/s)	Rit (N)	Rib (N)	Rit (N)	Rib (N)	Rit (N)	Rib (N)	Rit (N)	Rib (N)	Estimated Pressure
LATERAL 1									
0.115	155.7	116.0	167.0	127.3	167.6	127.9	157.2	117.5	59
0.230	189.4	143.2	217.3	171.1	203.4	157.2	179.8	133.6	118
LATERAL 2									
0.115	147.4	107.7	165.0	125.3	179.8	146.1	160.1	120.4	99
0.230	176.9	130.7	196.0	149.8	195.0	148.8	175.9	129.7	89

Table 5.1

SUMMARY OF CORRECTED RESISTANCE DATA

MODEL SPEED (m/s)	FREE Rit (N)	FREE Rib (N)	FREE Ris (N)	NORMAL Rit (N)	NORMAL Rib (N)	NORMAL Ris (N)	PRESSURED Rit (N)	PRESSURED Rib (N)	PRESSURED Ris (N)
LATERAL 1									
0.115	145.0	105.3	39.7	155.7	116.0	39.7	167.6	127.9	39.7
0.230	148.2	102.0	46.2	189.4	143.2	46.2	203.4	157.2	46.2
LATERAL 2									
0.115	142.0	102.3	39.7	147.4	107.7	39.7	179.8	140.1	39.7
0.230	156.5	110.3	46.2	176.9	130.7	46.2	195.0	148.8	46.2

AVERAGE DIFFERENCES FROM TNE NORMAL CONDITION

MODEL SPEED (m/s)	FREE Rit %	FREE Rib %	PRESSURED Rit %	PRESSURED Rib %
0.115	-5.312	-7.197	14.616	19.803
0.230	-16.817	-22.490	8.763	11.720

Appendix A

Abstracts of Relevant Papers

Database:	ASTIS	Record ID: 150630
Title:	Ice load prediction for arctic nearshore zone	
Author:	Vivatrat, V.; Chen, V.; Bruen, F.J.	
Source/Citation:	Cold regions science and technology, v. 10, no. 3, Nov. 1984, p. 75-87, ill.	
Major Topic:	Ice -- Except Glacier Ice and Ground Ice	
Geographic Area:	Arctic (General); Arctic Waters (General); Arctic regions	
Keywords:	Fast ice - Movement; Ice - Movement; Ice - Strain; Ice loads; Mathematical models; Offshore structures; Sea ice - Movement; Sea ice - Strain	
Abstract:	This paper presents a method for predicting the maximum ice force on indenters and man-made structures in the arctic nearshore zone. The proposed method relies on a power law to describe the rate-dependent behaviour of ice. It describes the ice movement pattern with a continuous-velocity field and estimates the total ice load with the bound theorem for creeping materials. The variation in the strain-rate from point to point can thus be taken into account. The fracture behavior of ice is considered by setting fracture limits on the strain-rate in compression and tension and modifying the energy dissipation terms in the zones in which the strain-rates exceed those limits. Predictions are made for the peak indentation pressure. This approach predicts that the ratio between the peak indentation pressure and the uniaxial compressive strength (Cx) will vary from about 2.9 at small penetration rates to about 1.5 at higher penetration rates. This reduction results directly from near-field crack formation. For application to man-made structures in the nearshore zone, the out-of-plane deformations in the ice are taken into account by setting limits on the extent of the near-field cracked zone. This approach predicts that, when the aspect ratio (structure diameter/ice thickness) is reasonably large, the maximum ice load will occur at a threshold ice velocity which is approximately equal for different structure sizes and which may be significantly less than the maximum ice load will occur at a threshold ice velocity which is approximately equal for different structure sizes and which may be significantly less than the maximum movement rate in the far field. These phenomena could not be predicted with existing predictive techniques. Predictions for typical structures are given. (Author)	
Notes:	References.	
Language:	English	
Publication Year:	1984	
Form of Work:	Serial Analytic	
Location:	Interlibrary Loans Office, Room 218, Library Tower, University of Calgary, Calgary, Alberta, Canada T2N 1N4. Telephone (403) 220-5967. Please give the ASTIS document number and full citation when ordering. Codes in parentheses following ACU indicate locations within the University of Calgary Libraries, and can be ignored by interlibrary loan customers.; Ocean Engineering Information Centre, Memorial University of Newfoundland, St. John's, Newfoundland, Canada A1B 3X5	

Database:	COLD REGIONS - CRREL Record ID: 38-002719
Title:	Plane-strain compressive strength of first year Beaufort Sea ice
Author:	Blanchet, D., et al; Hamza, H.
Source/Citation:	p.84-96 International Conference on Port and Ocean Engineering under Arctic Conditions, 7th, Helsinki, Finland , April 5-9, 1983. Proceedings, Vol.3 Espoo, Valtion teknillinen tutkimuskeskus, 1983; 4 refs.
Keywords:	Ice crystal structure; Ice loads; Tests; Ice strength; Sea ice; Offshore structures; Ice pressure; Compressive properties; Strains; Loads (forces)
Language:	English
Publication Year:	1983
Publication Date:	1983, July
Form of Work:	conference paper, comp. article
COLD Record ID:	38-002719

Database:	ASTIS Record ID: 130001
Title:	Ice forces on model marine structures
Author:	Haynes, F.D.; Sodhi, D.S.
Corp. Author:	International Conference on Port and Ocean Engineering Under Arctic Conditions, 7th, Helsinki, Finland, 5-9 Apr., 1983
Source/Citation:	The Seventh International Conference on Port and Ocean Engineering Under Arctic Conditions. - Espoo, Finland: Technical Research Centre of Finland, 1983, v. 2, p. 778-787, figures
Major Topic:	Ice -- Except Glacier Ice and Ground Ice; Engineering and Construction
Geographic Area:	Other or None
Keywords:	Ice loads - Testing; Models; Offshore structures
Abstract:	Small-scale laboratory experiments were conducted on model marine structures in the CRREL test basin. The experiments were performed by pushing model ice sheets against structures and monitoring the ice forces during the ice-structure interaction. The parameters, varied during the test program, were the geometry of the marine structure and the velocity, thickness, and flexural strength of the ice. The results are presented in the form of ice forces on sloping and vertical structures with different geometries. During ice action on sloping structures, a phenomenon of transition of failure mode from bending to crushing was observed as the ice velocity was steadily increased. (Author)
Notes:	References.
Language:	English
Publication Year:	1983
Form of Work:	Serial Analytic
Location:	Ocean Engineering Information Centre, Memorial University of Newfoundland, St. John's, Newfoundland, Canada A1B 3X5

Database: ASTIS Record ID: 129585

Title: Confined compressive strength of sea ice

Author: Timco, G.W.; Frederking, R.

Corp. Author: International Conference on Port and Ocean Engineering Under Arctic Conditions, 7th, Helsinki, Finland, 5-9 Apr., 1983

Source/Citation: The Seventh International Conference on Port and Ocean Engineering Under Arctic Conditions. - Espoo, Finland: Technical Research Centre of Finland, 1983, v. 1, p. 243-253, figures; DBR paper, no. 1152; NRCC - National Research Council of Canada, no. 22807

Major Topic: Ice -- Except Glacier Ice and Ground Ice

Geographic Area: Beaufort Sea

Keywords: Ice crystals - Structure; Sea ice - Strength; Sea ice - Stresses

Abstract: The confined compressive strength has been measured for both vertical (A-type) and lateral (B-type) confinement conditions for sea ice from the Beaufort Sea. The results show that the confined compressive strength is extremely sensitive to the structure of the ice. For granular ice, the confined compressive strength for both A and B type confinement is 19% higher than for unconfined compressive strength. For columnar ice, the compressive strength for A-type confinement can be four times as high as the strength of unconfined or B-type confined compressive strength. These results are explained in terms of basal-plane glide in the ice. The results of the tests are used to evaluate the coefficients of an n-type yield function from plasticity theory. The functional form of the yield surface for the cases of plane strain and plane stress in the plane of the ice cover are presented and compared to the corresponding functions for freshwater ice. (Author)

Notes: References.

Language: English

Publication Year: 1983

Form of Work: Serial Analytic

Location: Ocean Engineering Information Centre, Memorial University of Newfoundland, St. John's, Newfoundland, Canada A1B 3X5; Interlibrary Loans Office, Room 218, Library Tower, University of Calgary, Calgary, Alberta, Canada T2N 1N4. Telephone (403) 220-5967. Please give the ASTIS document number and full citation when ordering. Codes in parentheses following ACU indicate locations within the University of Calgary Libraries, and can be ignored by interlibrary loan customers.

Database:	ASTIS	Record ID: 130257
Title:	Estimation of the compressive strength of sea ice by the Schmidt test hammer	
Author:	Tsutae, S.; Itoh, Y.; Izumi, K.; Ono, T.; Saeki, H.	
Corp. Author:	International Conference on Port and Ocean Engineering Under Arctic Conditions, 7th, Helsinki, Finland, 5-9 Apr., 1983	
Source/Citation:	The Seventh International Conference on Port and Ocean Engineering Under Arctic Conditions. - Espoo, Finland: Technical Research Centre of Finland, 1983, v. 2, p.1080-1089, figures, tables	
Major Topic:	Ice -- Except Glacier Ice and Ground Ice	
Geographic Area:	Other or None	
Keywords:	Mathematical models; Sea ice - Strength; Sea ice - Strength - Testing	
Abstract:	It is very useful for the advancement of ice engineering if the compressive strength of sea ice can be measured easily without conducting conventional compressive tests in the laboratory. This paper aims to accurately estimate the uniaxial compressive strength of sea ice using the PT-Type Schmidt test hammer which heretofore has been used only for estimating the strength of concrete. This paper first discusses the optimum testing conditions required when using the Schmidt test hammer for sea ice. Next, a formula for estimating sea ice compressive strength is proposed as the function of the rebound number of Schmidt hammer test. (Author)	
Notes:	References.	
Language:	English	
Publication Year:	1983	
Form of Work:	Serial Analytic	
Location:	Ocean Engineering Information Centre, Memorial University of Newfoundland, St. John's, Newfoundland, Canada A1B 3X5	

Database: COLD REGIONS - CRREL Record ID: 33-001521

Title: On the determination of horizontal forces a floating ice plate exerts on a structure

Author: Kerr, A.D.

Source/Citation: U.S. Army Cold Regions Research and Engineering Laboratory Aug. 1978 9p. ADA-060 444; 26 refs. For this report from a different source see 32-4451.

Keywords: Floating ice; Ice pressure; Loads (forces); Offshore structures; Ice strength

Abstract: This report first discusses the general approach for calculating horizontal forces an ice cover exerts on a structure. Ice force determination consists of two parts: (1) the analysis of the in-plane forces, assuming that the ice cover remains intact, and (2) the use of a failure criterion, since an ice force cannot be larger than the force capable of breaking up the ice cover. For an estimate of the largest ice force, an elastic plate analysis and a failure criterion are often sufficient. A review of the literature revealed that, in the majority of the analyses, it is assumed that the failure load is directly related to a "crushing strength" of the ice cover. However, observations in the field and tests in the laboratory show that in some instances the ice cover fails by buckling. This report reviews the ice force analyses based on the buckling failure mechanism and points out their shortcomings. The report then presents a new method of analysis which is based on the buckling mechanism.

Language: English
Publication Year: 1978
Publication Date: 1978, August
Form of Work: technical report; journal article
CRREL Report #: CR 78-15
COLD Record ID: 33-001521

Database: ASTIS Record ID: 150630

Title: Ice load prediction for arctic nearshore zone

Author: Vivatrat, V.; Chen, V.; Bruen, F.J.

Source/Citation: Cold regions science and technology, v. 10, no. 3, Nov. 1984, p. 75-87, ill.

Major Topic: Ice -- Except Glacier Ice and Ground Ice

Geographic Area: Arctic (General); Arctic Waters (General); Arctic regions

Keywords: Fast ice - Movement; Ice - Movement; Ice - Strain; Ice loads; Mathematical models; Offshore structures; Sea ice - Movement; Sea ice - Strain

Abstract: This paper presents a method for predicting the maximum ice force on indenters and man-made structures in the arctic nearshore zone. The proposed method relies on a power law to describe the rate-dependent behaviour of ice. It describes the ice movement pattern with a continuous-velocity field and estimates the total ice load with the bound theorem for creeping materials. The variation in the strain-rate from point to point can thus be taken into account. The fracture behavior of ice is considered by setting fracture limits on the strain-rate in compression and tension and modifying the energy dissipation terms in the zones in which the strain-rates exceed those limits. Predictions are made for the peak indentation pressure. This approach predicts that the ratio between the peak indentation pressure and the uniaxial compressive strength (Cx) will vary from about 2.9 at small penetration rates to about 1.5 at higher penetration rates. This reduction results directly from near-field crack formation. For application to man-made structures in the nearshore zone, the out-of-plane deformations in the ice are taken into account by setting limits on the extent of the near-field cracked zone. This approach predicts that, when the aspect ratio (structure diameter/ice thickness) is reasonably large, the maximum ice load will occur at a threshold ice velocity which is approximately equal for different structure sizes and which may be significantly less than the maximum ice load will occur at a threshold ice velocity which is approximately equal for different structure sizes and which may be significantly less than the maximum movement rate in the far field. These phenomena could not be predicted with existing predictive techniques. Predictions for typical structures are given. (Author)

Notes: References.

Language: English

Publication Year: 1984

Form of Work: Serial Analytic

Location: Interlibrary Loans Office, Room 218, Library Tower, University of Calgary, Calgary, Alberta, Canada T2N 1N4. Telephone (403) 220-5967. Please give the ASTIS document number and full citation when ordering. Codes in parentheses following ACU indicate locations within the University of Calgary Libraries, and can be ignored by interlibrary loan customers.; Ocean Engineering Information Centre, Memorial University of Newfoundland, St. John's, Newfoundland, Canada A1B 3X5

Database: COLD REGIONS - CRREL Record ID: 32-004451

Title: On the determination of horizontal forces a floating ice plate exerts on a structure

Author: Kerr, A.D.

Source/Citation: Journal of glaciology 1978; 20(82) p.123-134; 26 refs.

Keywords: Floating ice; Ice pressure; Ice loads; Ice cover strength; Structures; Loads (forces)

Abstract: At first, the general approach for calculating the horizontal forces an ice cover exerts on structures is discussed. Ice-force determination consists of two parts: (1) the analysis of the in-plane forces, assuming that the ice cover remains intact; and (2) the use of a failure criterion, because an ice force cannot be larger than the force capable of breaking up the ice cover. For an estimate of the largest ice force, an elastic plate analysis and a failure criterion are often sufficient. A review of the literature revealed that in the majority of the analyses, it is assumed that the failure load is directly related to a "crushing strength" of the ice cover. Observations in the field and tests in the laboratory show, however, that in some instances the ice cover failed by buckling. Subsequently, the ice-force analyses based on the buckling failure mechanism are reviewed, and their shortcomings are pointed out. A new method of analysis, which is based on the buckling of a floating ice wedge, is then presented.

Language: English

Publication Year: 1978

Publication Date: 1978, July

Form of Work: journal article; journal article

CRREL Report #: MP 879

COLD Record ID: 32-004451

Database:	SPRI	Record ID: 13619
Title:	Ice-shelf backpressure: form drag versus dynamic drag.	
Author:	MacAyeal, Douglas R.; Veen, Cornelis J. van der; Oerlemans , Johannes, eds.	
Source/Citation:	Dynamics of the west Antarctic ice sheet. Proceedings of a Workshop held in Utrecht, May 6-8, 1985.; D. Reidel Publishing Co.; Dordrecht; :141-160, diags., tables; 1987	
Major Topic:	Glaciology: land ice, glaciers, iceshelves	
Geographic Area:	Antarctic regions; Byrd Land	
Keywords:	Ice shelves; Glaciers, flow. Theory; Land ice, miscellaneous forms	
Abstract:	Defines ice-shelf back-pressure in terms of depth-integrated force exerted by ice shelf across material plane cutting vertically through ice at grounding line of ice stream. Examines relationship between back-pressure and two factors restricting ice-shelf flow: form drag and dynamic drag. Demonstrates potential changes of back-pressure at grounding line of Ice Stream B as result of impulsive removal of Crary Ice Rise.	
Publication Year:	1987	
Location:	Shelf 551.324.24	

Database: COLD REGIONS - CRREL Record ID: 39-002409

Title: Quantitative analysis of ice sheet failure against an inclined plane

Author: Frederking, R.M.W., et al; Timco, G.W.

Source/Citation: p.160-169 International Offshore Mechanics and Arctic Engineering Symposium, 4th, Dallas, Texas, Feb. 17-21, 1985. Proceedings, Vol.2 New York, American Society of Mechanical Engineers, 1985; 10 refs.

Keywords: Floating ice; Ice pressure; Mathematical models; Ice cracks; Ice sheets; Offshore structures; Flexural strength; Ice breaking; Ice solid interface; Ice loads

Language: English

Publication Year: 1985

Publication Date: 1985, February

Form of Work: conference paper, comp. article

COLD Record ID: 39-002409

Database:	COLD REGIONS - CRREL Record ID: 43-003743
Title:	Deformation of floating ice sheets of variable thickness under in-plane compressive loading
Author:	Takeuchi, T., et al; Shapiro, L.H.
Source/Citation:	p.385-407 International Conference on Port and Ocean Engineering under Arctic Conditions, 10th, Luleå, Sweden, June 12-16, 1989. Proceedings. POAC 89. Vol.1. Edited by K.B.E. Axelsson and L.Å. Fransson Luleå, Sweden, University of Technology, 1989; 5 refs.
Keywords:	Floating ice; Ice models; Ice pressure; Ice mechanics; Ice cover thickness; Ice floes; Ice deformation; Ice loads
Language:	English
Publication Year:	1989
Publication Date:	1989, June
Form of Work:	conference paper, comp. article
COLD Record ID:	43-003743

Database: C-CORE Record ID: C00008-10-BG
Title: THE DEFORMATION OF FLOATING ICE SHEETS OF VARIABLE THICKNESS UNDER IN PLANE COMPRESSIVE LOADING
Author: Takeuchi, T; Shapiro, LH
Source/Citation: POAC 89. Proceedings, 10th, Lulea, Sweden, 1989; p.385-407
Keywords: ice floes; ice deformation; ice loads; floating ice; ice models; ice pressure; ice mechanics; ice cover thickness
Form of Work: Conference Paper
Location: NFSMO

Appendix B

Measured Ice Properties

NRC - INSTITUTE FOR MARINE DYNAMICS

ARCTIC VESSEL RESEARCH SECTION

ICE SHEET SUMMARY

Test Name: LATERAL1

Project Number: 92304

Target ice thickness(mm): 80.

EG/AD/S: (%) .39/.036/.04

Target ice strength(kPa): 30

Ice Type: M

SEEDING:

Air temp.(max/min) C: -19.3/-14.3
Seeding completed at 1335 5-FEB-1992
Seed volume: l 33.5
Humidity: tank(%) 73
room(%) 39

Tank water temp. C: 0.12
Seed duration: (min) 30.
Seed water temp.: C 55.0

GROWTH:

Target temp.: C -20.0
Avg temp. at plateau: C -20.3
Avg temp. of freeze cycle C -20.2
Total negative deg. hours 632.2
Avg growth rate: (mm/hr) 2.211

Time to target temp. hrs: 1.3
Duration of plateau hrs: 30.1
Duration of freeze cycle hrs: 31.4
Thickness at end of freeze:(mm) 69.4
Avg growth rate: (mm/fdh) .110

WARM-UP:

Warm-up commenced at 2057 6-FEB-1992
Time to tempering temp: (hrs) 3.7
Final ice thickness: (mm) 78.1
Total growth rate: (mm/hr) 2.490

Length of warm-up: (hrs) 19.
Avg tempering temperature: (C) 2.2
Ice growth during warm-up: (mm) 8.7
Total growth rate: (mm/fdh) .124

* thickness at end of freeze was estimated

NRC - INSTITUTE FOR MARINE DYNAMICS

ARCTIC VESSEL RESEARCH SECTION

ICE MECHANICAL PROPERTIES SUMMARY

Test Name: LATERAL1 **Project Number: 92304**

Warm up commenced: 20:57 6-FEB-1992

Time	Warm-up hrs	Loc	hi mm	Sf kPa	Lc cm	E MPa	E/Sf	Lc/hi	K1c N/m	Sf/K1c m-.5	Sc/s kPa	Rhoi Mg/m3
0835	11.63	N	78.3± 1.8 n= 2									
		S	77.3± 0.4 n= 2									
0845	11.80	40S	77.5		101.	234.5	3740	13.0				
0905	12.13	40N	77.7	60.± 3.8								
			77.3	50.(u/d 83%)								
0907	12.17	40S	76.8	61.± 3.1								
			77.7	56.(u/d 92%)								
1026	13.48	39N	78.1	54.± 2.3								
			78.2	47.(u/d 87%)								
1028	13.52	39S	77.6	56.± 5.2								
			77.7	46.(u/d 81%)								
1036	13.65	39N	78.0							c	229.7±40.8	
1047	13.83	39S	77.9							s	79.9± 5.7	
1218	15.35	37N	78.2	44.± 2.4								
			78.1	37.(u/d 82%)								
1220	15.38	37S	77.3	45.± 3.6								
			77.2	34.(u/d 75%)								
1333	16.60	36S	77.1	42.± 2.6								
			77.2	27.(u/d 63%)								
		36N	77.5									.931
1334	16.62	36N	77.3	40.± 1.7								
			77.8	24.(u/d 60%)								
1350	16.88	36N	77.5							c	170.1±25.0	
1424	17.45	35N	77.0	38.± 2.8								
			77.0	22.(u/d 57%)								
1426	17.48	35S	76.3	38.± 1.2								

			76.7	21.(u/d 56%)
1547	18.83	34S	75.8	36.± 0.7
			75.9	17.(u/d 47%)
1549	18.87	34N	76.1	31.± 1.4
			76.0	22.(u/d 69%)
1553	18.93	N	77.6± 2.2 n=33	
		S	77.7± 2.8 n=33	

NATIONAL RESEARCH COUNCIL - INSTITUTE FOR MARINE DYNAMICS

ICE SHEET PROPERTIES AND LOCATION DIAGRAM

ICE SHEET: LATERAL 1 DATE: 7 FEBRUARY 1992

TEST-TIME: 1436

Flexural strength @ Test-time

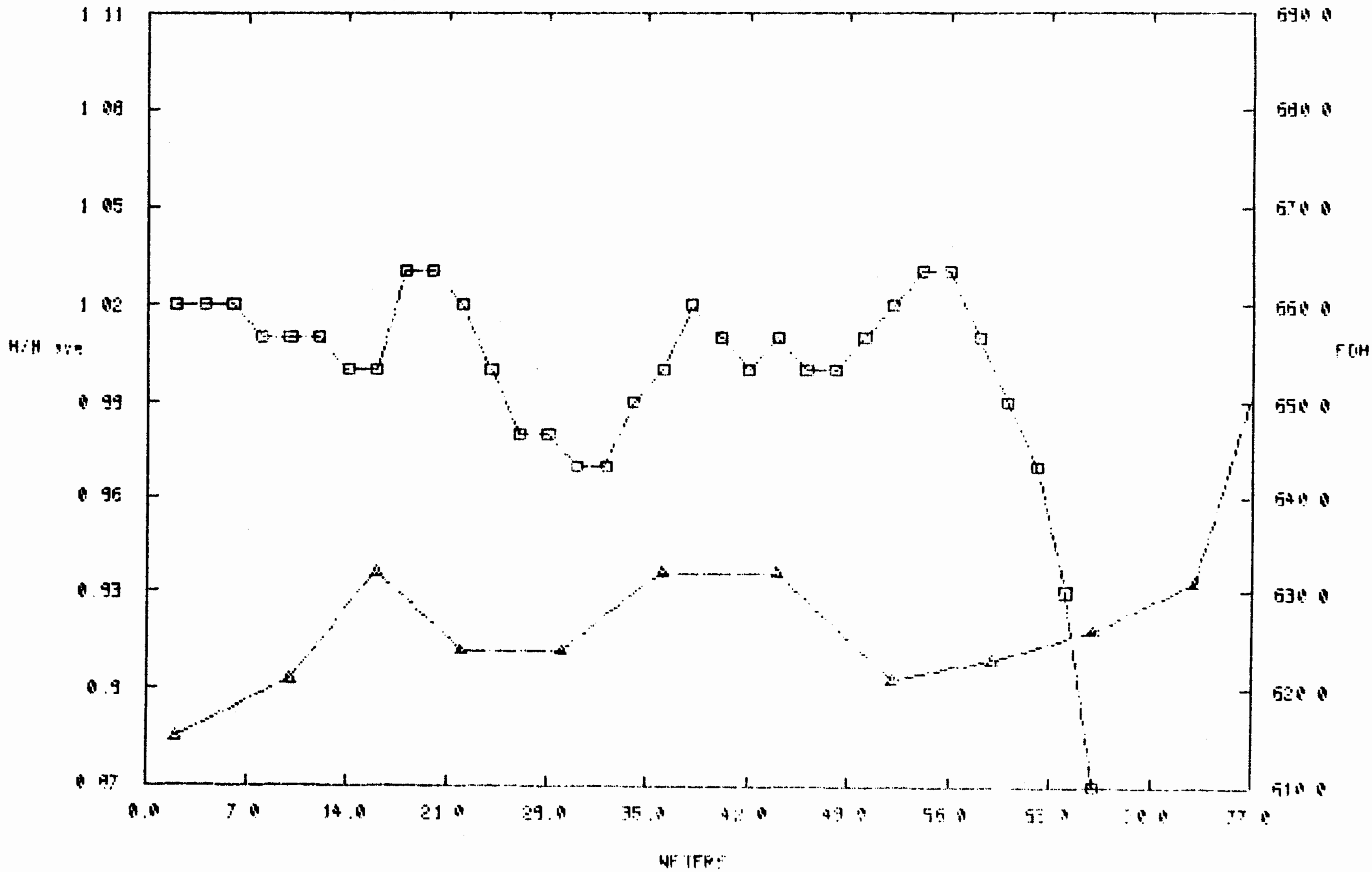
Position			
0			
5			
10			
15 / 16	37 ± 1	37 ± 1	AVE σ_f : 37 ± 1 kPa ; n = 6. h : 78.2 ± 1.4 mm ; n = 30
20			
25			
30			
NORTH 35	38 ± 3	38 ± 1	AVE σ_f : 38 ± 2 ; n = 8 h : 77.7 ± 1.3 ; n = 22
40			
45			
50	35 ± 0.6	34 ± 0.9	AVE σ_f : 35 ± 1 ; n = 6 BEFORE PRESSURE
51	32 ± 3	33 ± 3	AVE σ_f : 33 ± 3 ; n = 6 AFTER PRESS.
55			
59 / 60	33 ± 3	34 ± 2	AVE σ_f : 33 ± 2 ; n = 6 " "
65			
70			

AVE FOR PRESSURED TEST AREA

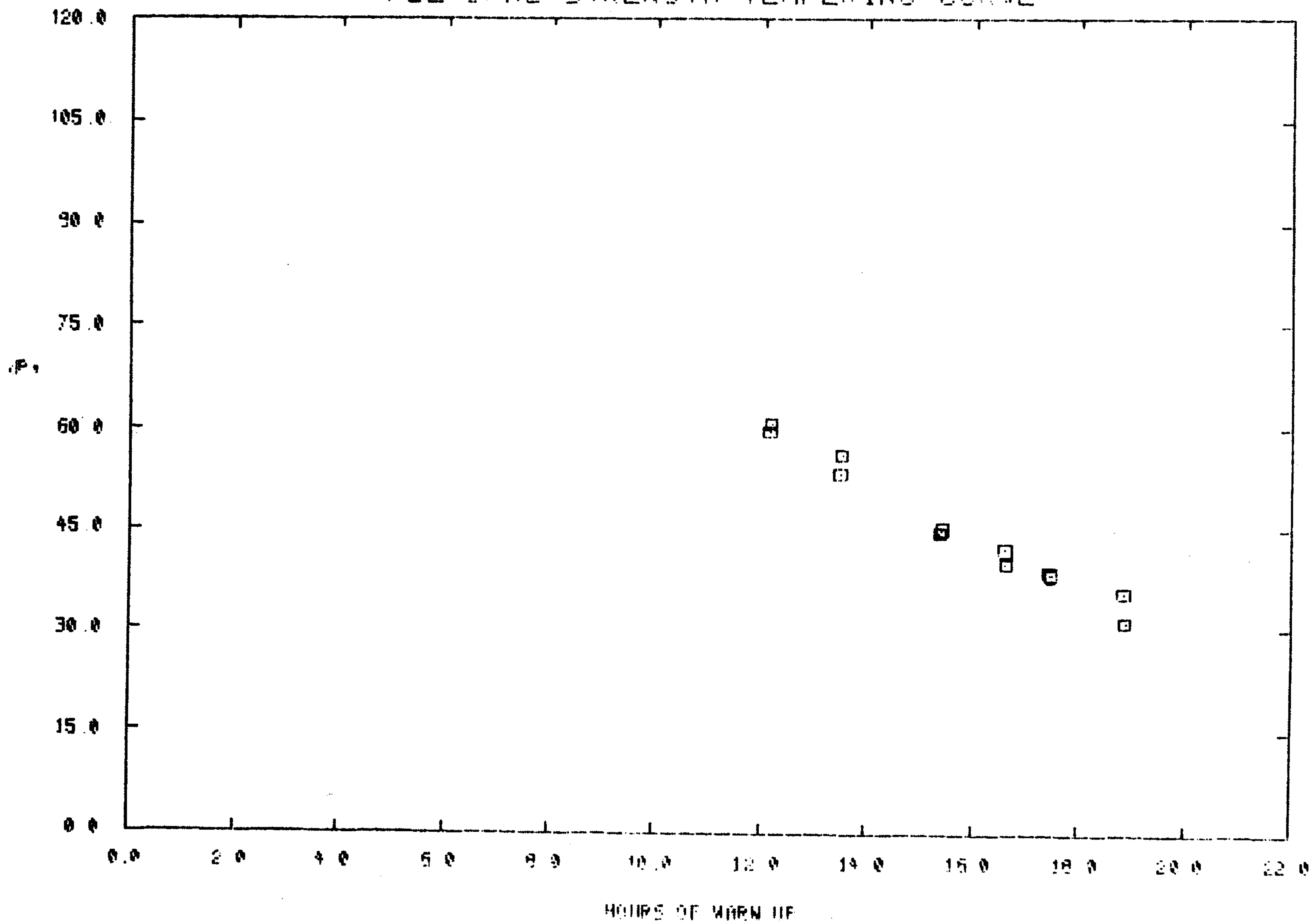
σ_f : 33 ± 2 kPa ; n = 18

h : 77.6 ± 2.7 mm ; n = 16.

ICE THICKNESS PROFILE - CENTER CHANNEL



FLEXURAL STRENGTH TEMPERING CURVE



NRC - INSTITUTE FOR MARINE DYNAMICS

ARCTIC VESSEL RESEARCH SECTION

ICE THICKNESS

st Name: LATERAL1

roject Number: 92304

ite: 02/07/92

ime: 0825

center profile

Tank Position(m)	Thickness(mm) north	south
20.0	79.6	77.0
40.0	77.0	77.6
mean	78.3	77.3
std dev	1.8	0.4
# samples	2	2

he mean ice thickness from 20.m to 40.m is 77.8 mm s.d.= 1.2

ate: 02/07/92

ime: 1553

center profile

Tank Position(m)	Thickness(mm) north	south
2.0	79.2	79.2
4.0	79.3	79.4
6.0	79.0	78.9
8.0	78.8	78.7
10.0	79.3	77.9
12.0	78.8	77.5
14.0	78.2	77.3
16.0	77.9	77.7
18.0	79.5	80.7
20.0	80.2	79.5
22.0	79.4	78.9
24.0	77.7	78.3
26.0	76.3	76.3
28.0	76.0	76.1
30.0	75.1	76.3
32.0	75.3	75.7
34.0	76.1	77.5
36.0	77.4	77.7
38.0	79.5	78.7
40.0	78.4	78.8
42.0	77.4	78.6
44.0	77.6	79.7
46.0	77.4	78.3
48.0	77.1	78.5
50.0	77.9	79.6
52.0	79.6	79.5

56.0	79.9	79.9
58.0	78.1	78.2
60.0	76.6	77.9
62.0	75.7	74.6
64.0	74.7	70.2
66.0	69.1	65.6
mean	77.6	77.7
std dev	2.2	2.8
# samples	33	33

he mean ice thickness from 2.m to 66.m is 77.6 mm s.d.= 2.5

he mean ice thickness from 2.m to 30.m is 78.2 mm s.d.= 1.4

he mean ice thickness from 2.m to 15.m is 78.7 mm s.d.= 0.7

The mean ice thickness from 15.m to 30.m is 77.9 mm s.d.= 1.6

he mean ice thickness from 30.m to 50.m is 77.7 mm s.d.= 1.3

he mean ice thickness from 30.m to 40.m is 77.2 mm s.d.= 1.5

he mean ice thickness from 40.m to 50.m is 78.3 mm s.d.= 0.8

he mean ice thickness from 50.m to 64.m is 77.6 mm s.d.= 2.7

he mean ice thickness from 50.m to 57.m is 79.5 mm s.d.= 0.7

he mean ice thickness from 57.m to 64.m is 76.6 mm s.d.= 2.9

he mean ice thickness from 0.m to 62.m is 78.1 mm s.d.= 1.4

NRC - INSTITUTE FOR MARINE DYNAMICS

ARCTIC VESSEL RESEARCH SECTION

ICE SHEET SUMMARY

Test Name: LATERAL2

Project Number: 92304

Target ice thickness(mm): 80.

EG/AD/S: (%) .39/.036/.04

Target ice strength(kPa): 30

Ice Type: M

SEEDING:

Air temp.(max/min) C: -19.1/-15.6
Seeding completed at 1130 11-FEB-1992
Seed volume: l 28.8
Humidity: tank(%) 71
room(%) 34

Tank water temp. C: 0.01
Seed duration: (min) 30.
Seed water temp.: C 35.0

GROWTH:

Target temp.: C -20.0
Avg temp. at plateau: C -19.9
Avg temp. of freeze cycle C -19.8
Total negative deg. hours 634.0
Avg growth rate: (mm/hr) 2.284

Time to target temp. hrs: 1.7
Duration of plateau hrs: 30.4
Duration of freeze cycle hrs: 32.0
Thickness at end of freeze:(mm) 73.2
Avg growth rate: (mm/fdh) .115

WARM-UP:

Warm-up commenced at 1932 12-FEB-1992
Time to tempering temp: (hrs) 3.8
Final ice thickness: (mm) 80.6
Total growth rate: (mm/hr) 2.515

Length of warm-up: (hrs) 19.
Avg tempering temperature: (C) 2.2
Ice growth during warm-up: (mm) 7.4
Total growth rate: (mm/fdh) .127

* thickness at end of freeze was estimated

NRC - INSTITUTE FOR MARINE DYNAMICS

ARCTIC VESSEL RESEARCH SECTION

ICE MECHANICAL PROPERTIES SUMMARY

Test Name: LATERAL2 **Project Number:** 92304

Warm up commenced: 19:32 12-FEB-1992

Time	Warm-up hrs	Loc	hi mm	Sf kPa	Lc cm	E MPa	E/Sf	Lc/hi	K1c N/m	Sf/K1c m-.5	Sc/s kPa	Rhoi Mg/m3
0830	12.95	N	81.0± 2.8 n= 3									
		S	83.0± 1.9 n= 3									
0845	13.20	40S	78.6		98.	199.0	3540	12.4				
0903	13.50	40N	77.8	55.± 2.9								
			78.6	42.(u/d 76%)								
0905	13.53	40S	78.7	54.± 0.3								
			78.9	43.(u/d 79%)								
1033	15.00	39N	78.6	45.± 0.9								
			78.8	34.(u/d 75%)								
1036	15.05	39S	78.9	47.± 1.3								
			79.3	40.(u/d 86%)								
1120	15.78	39N	79.0								c 172.3±15.4	
1128	15.92	39S	78.8								s 65.7± 7.6	
1229	16.93	38N	79.3	40.± 1.4								
			79.0	30.(u/d 76%)								
1231	16.97	38S	79.6	40.± 2.8								
			80.2	32.(u/d 79%)								
1336	18.05	37N	79.8	35.± 1.5								
			79.2	25.(u/d 71%)								
1338	18.08	37S	79.6	31.± 0.8								
			79.4	46.(u/d147%)								
1445	19.20	36S	79.1	33.± 0.9								
			79.2	21.(u/d 62%)								
		N	80.7± 1.6 n=33									
		S	80.5± 1.4 n=33									
1447	19.23	36N	80.3	31.± 1.7								
			80.5	21.(u/d 67%)								
1450	19.28	36S	79.4									.932

NATIONAL RESEARCH COUNCIL - INSTITUTE FOR MARINE DYNAMICS

ICE SHEET PROPERTIES AND LOCATION DIAGRAM

ICE SHEET: LATERAL 2

DATE: 13 FEBRUARY 1992

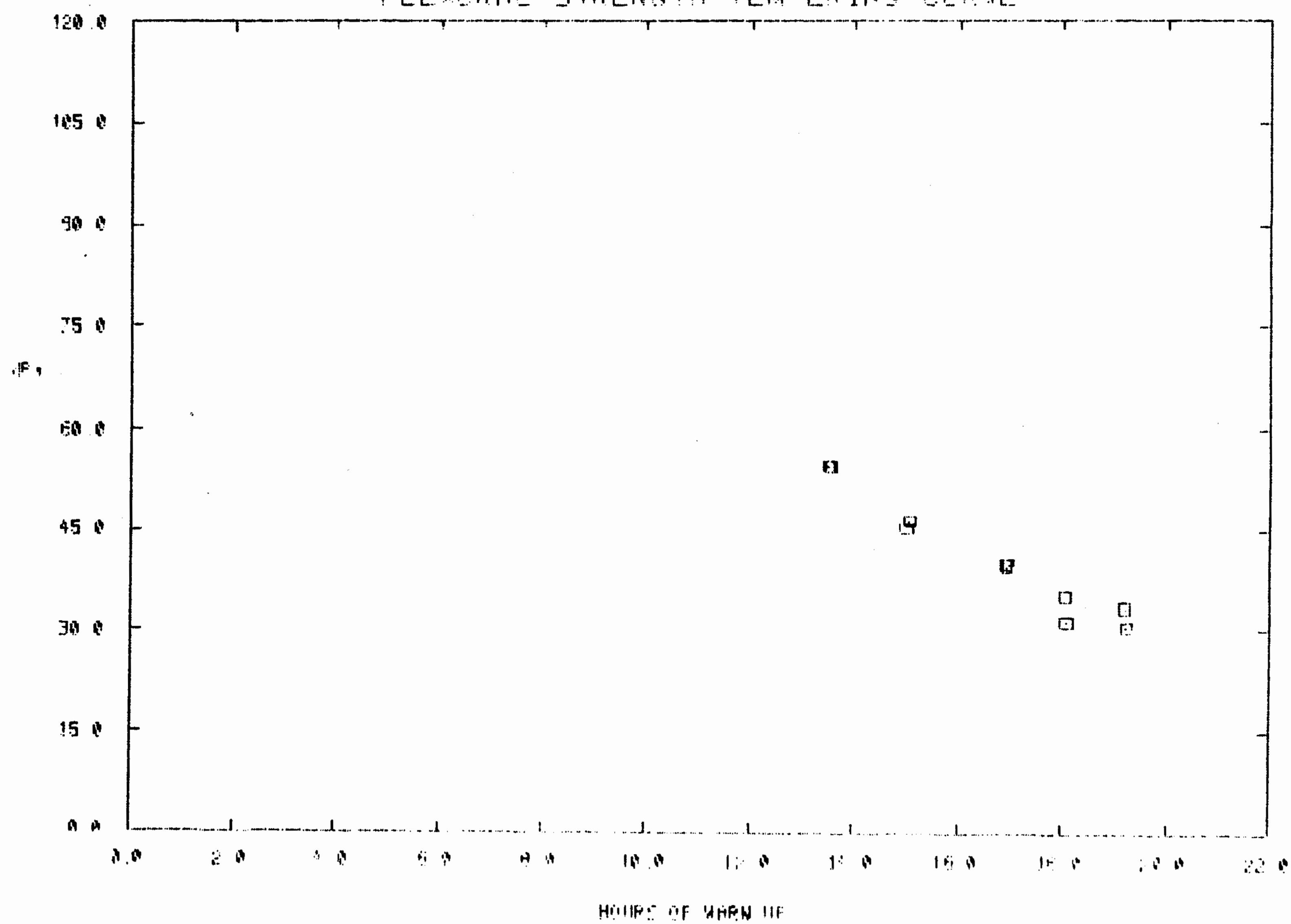
TEST-TIME: 1411

NORTH

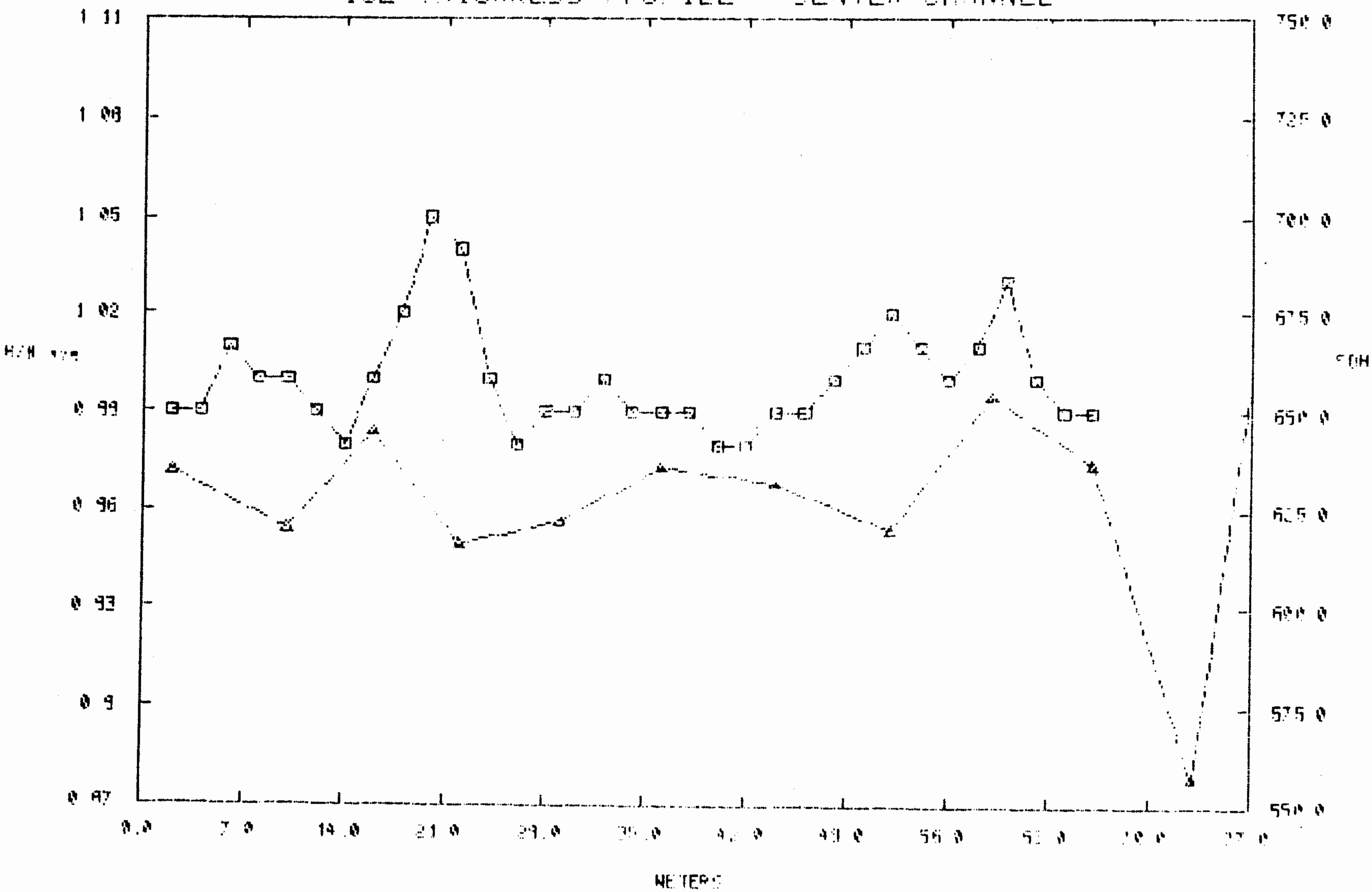
	Flexural strength @ Test-time		
0–15			
15–30 (24/25)	35 ± 1	36 ± 3	AVE. δ_f = 36 ± 2 kPa ; n = 6 h = 81.2 ± 1.8 mm ; n = 18
30–50	33 ± 1	30 ± 0.8	AVE. δ_f : 31 ± 2 ; n = 8 h : 79.9 ± 0.8 ; n = 20
50–66 (55/57)	31 ± 0.8	30 ± 2	TEST-TIME: 1427 AVE. δ_f = 30 ± 1 ; n = 6 h : 81.1 ± 1.6 ; n = 18
66–70			

0 5 10 15 20 24 25 30 35 40 45 50 55 57 60 65 70

FLEXURAL STRENGTH TEMPERING CURVE



ICE THICKNESS PROFILE - CENTER CHANNEL



NRL - INSTITUTE FOR MARINE DYNAMICS

ARCTIC VESSEL RESEARCH SECTION

ICE THICKNESS

et Name: LATERAL2

roject Number: 92304

ate: 02/13/92

ime: 0830

center profile

Tank Position(m)	Thickness(mm) north	south
20.0	81.4	84.0
40.0	78.0	80.8
60.0	83.6	84.3
mean	81.0	83.0
std dev	2.8	1.9
# samples	3	3

e mean ice thickness from 20.m to 60.m is 82.0 mm s.d.= 2.4

ate: 02/13/92

ime: 1445

te: 02/13/92

ime: 1445

center profile

Tank Position(m)	Thickness(mm) north	south
2.0	79.3	80.0
4.0	79.7	80.2
6.0	81.2	81.1
8.0	81.7	79.5
10.0	81.6	79.3
12.0	79.6	80.4
14.0	79.6	79.1
16.0	81.1	80.4
18.0	82.0	82.2
20.0	84.7	84.0
22.0	84.3	83.2
24.0	80.7	81.2
26.0	79.5	79.0
28.0	79.3	80.0
30.0	80.0	80.3
32.0	80.2	80.3
34.0	79.5	80.2
36.0	80.0	79.9
38.0	79.2	79.9
40.0	78.6	79.4
[illegible]	[illegible]	[illegible]

44.0	[illegible]	[illegible]
46.0	79.7	80.6
48.0	80.3	80.3
50.0	81.4	81.7
52.0	81.5	82.4
54.0	81.1	82.3
56.0	82.3	78.4
58.0	83.5	79.0
60.0	83.0	83.1
62.0	79.7	81.8
64.0	80.2	78.7
66.0	79.7	79.9
mean	80.7	80.5
std dev	1.6	1.4
# samples	33	33

The mean ice thickness from 2.m to 66.m is 80.6 mm s.d.= 1.5

The mean ice thickness from 2.m to 48.m is 80.4 mm s.d.= 1.4

The mean ice thickness from 2.m to 10.m is 80.4 mm s.d.= 1.0

The mean ice thickness from 10.m to 16.m is 80.1 mm s.d.= 0.9

The mean ice thickness from 2.m to 16.m is 80.2 mm s.d.= 0.9

The mean ice thickness from 16.m to 24.m is 82.4 mm s.d.= 1.6

The mean ice thickness from 24.m to 40.m is 79.8 mm s.d.= 0.6

The mean ice thickness from 40.m to 48.m is 79.6 mm s.d.= 0.7

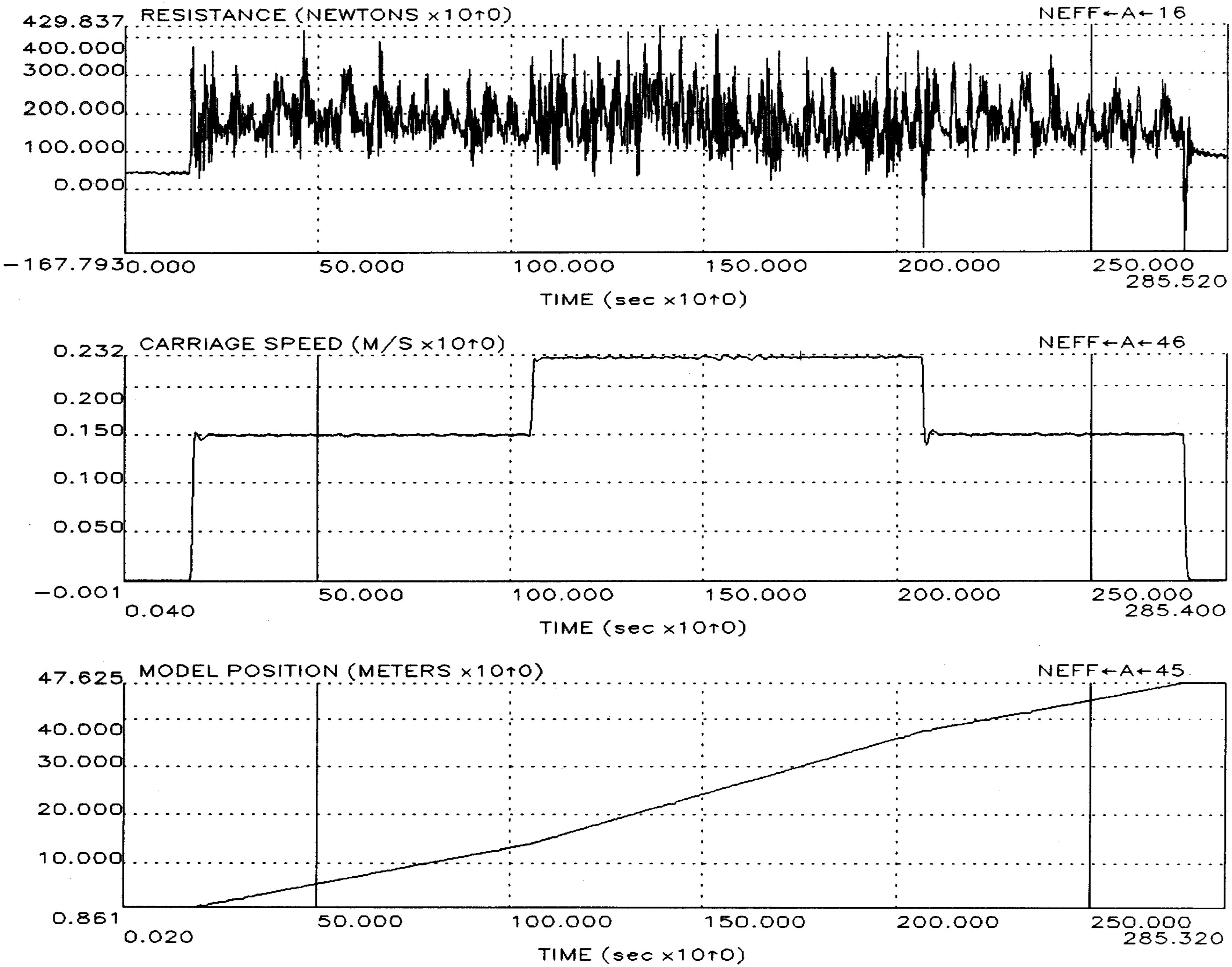
The mean ice thickness from 50.m to 66.m is 81.1 mm s.d.= 1.6

The mean ice thickness from 50.m to 58.m is 81.4 mm s.d.= 1.6

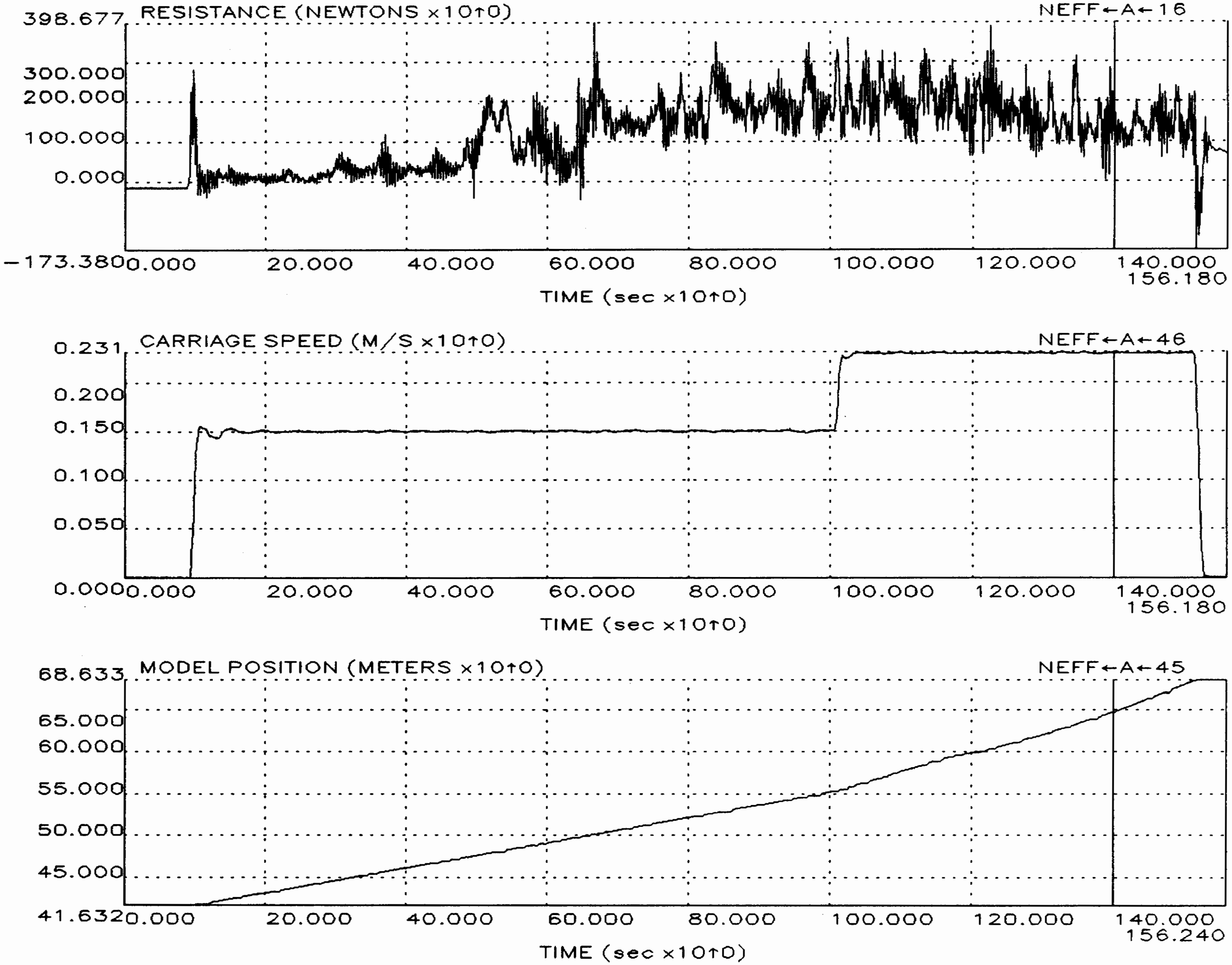
The mean ice thickness from 58.m to 66.m is 80.9 mm s.d.= 1.8

Appendix C

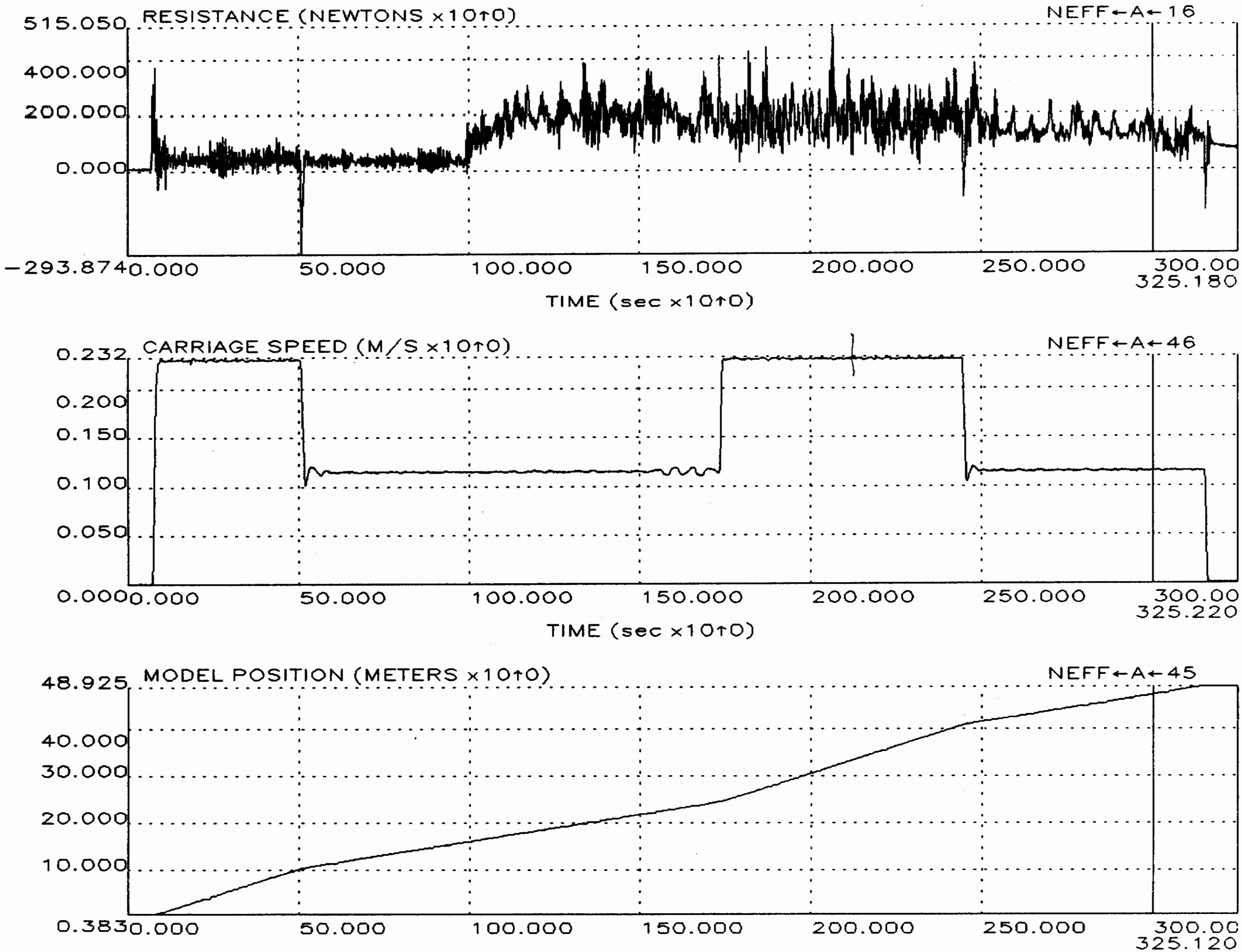
Time Series Plots



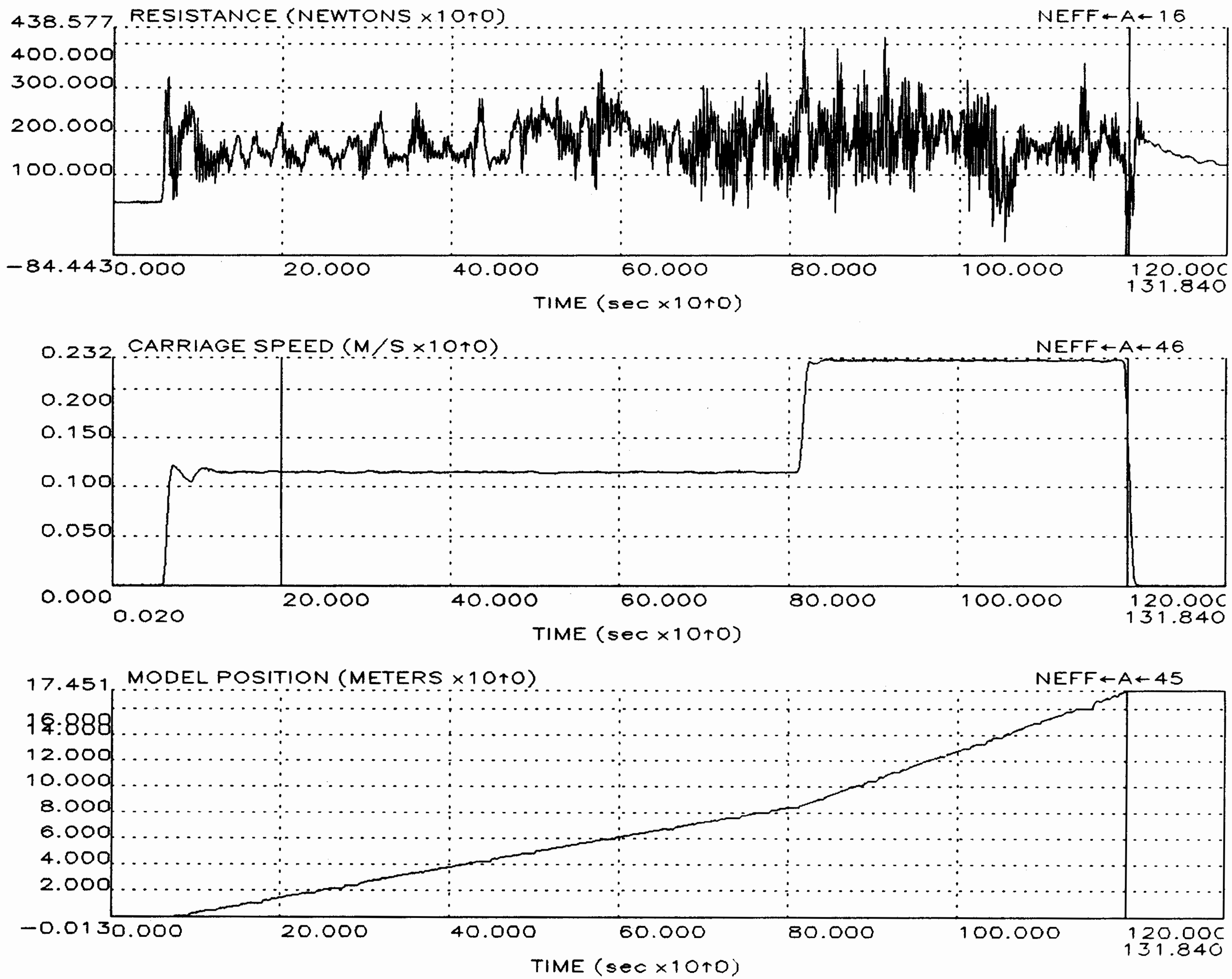
TEST←LATERAL1 RUN←1 7−FEB−1992 14:36:07



TEST←LATERAL1 RUN←2 7−FEB−1992 14:50:35



TEST←LATERAL2 RUN←1 13—FEB—1992 14:08:46



TEST←LATERAL2 RUN←2 13−FEB−1992 14:24:16